Exploring the Influence of Haptic Force Feedback on 3D Selection

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“To Manohar, Bharati and Sanjay”

I, Vijay Pawar, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

This thesis studies the effects of haptic force feedback on 3D interaction performance. To date, Human-Computer Interaction (HCI) in three dimensions is not well understood. Within platforms, such as Immersive Virtual Environments (IVEs), implementing 'good' methods of interaction is difficult. As reflected by the lack of 3D IVE applications in common use, typical performance constraints include inaccurate tracking, lack of additional sensory inputs, in addition to general design issues related to the implemented interaction technique and connected input devices. In total, this represents a broad set of multi-disciplinary challenges. By implementing techniques that address these problems, we intend to use IVE platforms to study human 3D interaction and the effects of different types of feedback.

A promising area of work is the development of haptic force feedback devices. Also called haptic interfaces, these devices can exert a desired force onto the user simulating a physical interaction. When described as a sensory cue, it is thought that this information is important for the selection and manipulation of 3D objects. To date, there are a lot of studies investigating how best to integrate haptic devices within IVEs. Whilst there are still fundamental integration and device level problems to solve, previous work demonstrates that haptic force feedback can improve 3D interaction performance. By investigating this claim further, this thesis explores the role of haptic force feedback on 3D interaction performance in more detail. In particular, we found additional complexities whereby different types of haptic force feedback conditions can either help but also hinder user performance. By discussing these new results, we begin to examine the utility of haptic force feedback.

By focusing our user studies on 3D selection, we explored the influence of haptic force feedback on the strategies taken to target virtual objects when using either 'distal' and 'natural' interaction technique designs. We first outlined novel methods for integrating and calibrating large scale haptic devices within a CAVE^{TM}-like IVE. Secondly, we described our implementation of distal and natural selection techniques tailored to the available hardware, including the collision detection mechanisms used to render different haptic responses. Thirdly, we discussed the evaluation framework used to assess different interaction techniques and haptic force feedback responses within a common IVE setup. Finally, we provide a detailed assessment of user performance highlighting the effects of haptic force feedback on 3D selection, which is the main contribution of this work. We expect the presented findings will add to the existing literature that evaluates novel 3D interaction technique designs for IVEs. We also hope that this thesis will provide a basis to develop future interaction models that include the effects of haptic force feedback.

Acknowledgements

As Winston Churchill wrote, "Writing is an adventure. To begin with, it is a toy and an amusement. Then it becomes a mistress, then it becomes a master, then it becomes a tyrant. The last phase is that just as you are about to be reconciled to your servitude, you kill the monster and fling him to the public". I would like to take this opportunity to acknowledge the contribution of a few individuals that have made this thesis possible. First and foremost, I owe a lot of gratitude to Prof. Anthony Steed. Without his patience and support I would not have achieved this milestone. I can only hope to repay his loyalty by sharing the successes of this work and any future endeavours.

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Chapter 1

Introduction

1.1 Motivation

One of the fundamental building blocks of any interactive system is the user interface for selecting objects. This is particularly important for Human Computer Interfaces (HCI), such as Immersive Virtual Environments (IVEs) where to manipulate a virtual object, the user must first select it. Selection, that is the specification of the object of interest is a common precursor to subsequent tasks [Ste06]. To date, a considerable amount of work has been done on the design of suitable interaction techniques that enable selection for IVEs. The most popular and commonly implemented examples include virtual hand and ray casting [BKLP05]. Even with these different design approaches, fundamental limitations remain that are detrimental to the usability of IVE platforms.

We can identify several factors that contribute to the performance of 3D selection techniques: the devices being used, the hand, and the type of setup. Investigations into other factors, such as the inclusion of additional sensory modalities are not well understood [SB97]. A promising area of work is the integration of haptic force feedback devices. Recent studies demonstrate the advantages of displaying haptic force feedback to user performance. In particular, researchers believe that these cues can help design more intuitive methods of interaction [ASFB02].

HCI studies that investigate haptic force feedback suggest that the extra bandwidth provided will benefit user performance. Starting from an information theory perspective such as Fitts' law, researchers argue that haptic force feedback will deliver more information to the user, and at a greater frequency. For example, as the latency of the haptic sensory loop is much less than visual cues, users will receive information from their surroundings fractionally earlier, helping their ability to perform tasks [Fit54]. However, from a mechanical point of view, haptic force feedback would also require users to put in more work as they either have to push through, or take longer paths to task completion, by avoiding virtual objects that provide a physical resistance. Due to this potential trade-off, we wish to outline these effects to help understand how to best incorporate haptic force feedback for better interactions within IVEs.

1.2 3D Selection within IVEs

To perform a 3D interaction within an IVE, we track and transform the user's body movements into actions represented by the connected display devices. At a basic level this model provides two elements:

a viewpoint and a cursor. The viewpoint is the point at which we consider the user to be within the IVE, providing a local reference frame in which we render the virtual environment [BKH97]. A cursor acts as an end effector that the user can use to select the surrounding 3D objects and perform subsequent tasks. This is similar to the model used for 2D interactions but extended to three dimensions.

Designers can choose from a vast number of methods to translate and display our body movements within an IVE. Work by Nielson et al. argues the benefits of implementing 3D interaction techniques that behave similar to how we perform tasks in the real world [JR90]. For example, users can perform interactions such as 3D selection, without having to learn a new method of moving to perform tasks. However, in some cases, this type of interaction can be completely inadequate. Depending on the application objectives, designers may also want to give users superhuman capabilities by extending their physical, perceptual and cognitive performance within the IVE, such as continuous 360-degree hand rotations, magnification of distant objects and selection with targets placed beyond arms reach [PWF00]. The advantages of using these 'non-realistic' or 'distal' interaction techniques is to improve task performance by overcoming known limitations of the user and the available hardware.

1.3 Haptic Force Feedback for better 3D Selection

Interfaces that simulate tactile and force feedback cues are useful for understanding aspects of an object's physical properties. Researchers have shown that haptic devices can benefit user performance for specific 3D applications (section 2.2). However, due to their mechanical complexity, this can reduce the types of compatible interactions to only a small subset of 3D movements or gestures (section 2.3).

Prior to the widespread availability of haptic devices researchers have experimented with augmenting the standard mouse with mixed results. As these devices have become more affordable, recent studies are investigating new ways of incorporating haptic force feedback cues to aid virtual reality applications (section 2.4). Common examples include assisting individuals that are visually impaired or whose mobility is limited. With respect to 3D interaction, Wall and Harwin showed that the use of force feedback with a 3D graphical display can improve performance in a Fitts' style tapping test [WH00].

Within HCI, research determining the effects of haptic force feedback is in its infancy. To date, there are only a few studies that include haptic devices within large scale IVE platforms [GASM08] [KR05] [MT00] [PS09] [DPL07]. In general, guidelines describing how best to incorporate haptic devices to improve specific interactions such as 3D selection remain underdeveloped.

1.4 Research Hypothesis

Our main research problem was to understand the effect of haptic feedback on 3D selection and task efficiency. To start, we wanted to build upon the state of the art and evaluate the effects of haptic force feedback on 3D interactions techniques commonly used within large scale IVEs. For the interaction techniques developed for this thesis, we believe that the combination of haptic and visual feedback will be superior to visual feedback when performing simple selection tasks (movement time (MT) to touch a single target). We also expect this trend to continue for other performance markers such as distance travelled (DT) and velocity taken (VT) (see section 1.7 for further terms and notations).

The second hypothesis was that this will no longer be true for complex selection tasks involving multiple targets. Rather than help selection performance, in this instance haptic force feedback will cause the user to take longer or slower paths to task completion after selecting the first target. A more formative hypothesis is that we expect the task efficiency when moving to select multiple targets to be dependent on the type of haptic force feedback displayed upon contact. More specify, this will be shown by changes in the selection strategies used for task completion. As there is little prior work in this area, we do not have any formal expectations in MT, DT and VT for each interaction technique evaluated in this thesis.

Ideally, within IVEs we wish to always support unbiased two handed interaction. Therefore, we include evaluations for both bi-manual and single handed interaction modes.

1.5 Scope

This thesis was concerned with the design, implementation and evaluation of haptic force feedback within IVEs. We integrated a large scale two handed haptic force feedback device into a CAVE^{TM}-like IVE system. By using this hardware setup, we investigated 3D selection performance throughout the full workspace of the user's arm length. Whilst previous studies into desktop-based haptic devices are informative, their results are not directly transferable due to the original design of the available equipment. Therefore, in order for the results presented in this thesis to be applicable to other IVE platforms, we developed a set of novel calibration techniques that accurately aligned the connected display devices so that participants were able to perform 3D interactions using common gestures (see section 3.3).

To evaluate different types of 3D selection techniques, we developed methods for accurately calibrating and co-locating the connected visual and haptic display devices to a 3D tracking system. This provided the flexibility to define a variety of spatial mappings and evaluate a range of distal and natural selection techniques to a high resolution. To help reduce the scope of this design space, we also started our exploration of haptic force feedback by first investigating commonly used interaction techniques within CAVE^{TM}-like IVEs.

The basic requirements of the implemented selection techniques were defined through consideration of the available hardware and their limitations. By running pilot tests, this approach also guided the design of the evaluation framework. Again, due to the immaturity of this research area, we started by building upon the state of the art with respect to user evaluations of 3D interactions in IVEs. From this, we then developed methods for recording different types of quantitative and qualitative performance markers by building upon our findings through the conducted experiments.

To help reduce the scope of the thesis, we focused our user studies to assess 3D selection only. We also developed collision detection methods that rendered force feedback upon intersection between the 3D haptic contact points and virtual objects only (section 3.3.3). As a result, we did not evaluate interaction techniques for object manipulation or render haptic feedback in 'novel' ways such as deformation, texture and other forms of contact.

1.6 Contributions

The main contribution of this thesis is:

- Analysis of selection strategies under different haptic force feedback conditions using:
    a. distal interaction techniques.
    b. natural interaction technique.

The minor contributions include:

- Methods for integrating two large scale haptic devices within a CAVE^{TM}-like IVE display system.
- Calibration protocols mapping the local coordinate frames of the connected display and tracking devices to a global temporal and spatial frame.
- Co-location of visual and haptic cues within a CAVE^{TM}-like IVE.
- Presentation of a testbed evaluation framework for assessing 3D selection performance.
- Implementation of distal and natural interaction techniques for 3D selection.
- Logging and analysis tools suitable for evaluating user performance of 3D selection tasks.

1.7 Terms and Notations

To improve readability, we used the following terms throughout this thesis:

- *Hard*- Hard force feedback condition.
- *Soft*- Soft force feedback condition.
- *NoF*- No force feedback condition.
- *Select1 / Select1,All / Sel1,A (term 'Sel' sometimes given as a shorthand for 'Select')*- Task completion to select one target.
- *Select2 / Select2,All / Sel2,A* - Task completion to select two targets.
- *Select2,1 / Sel2,1*- Selection of the first target from a set of two.
- *Select2,2 / Sel2,2*- Selection of the second target from a set of two.
- *Select3 / Select3,All / Sel3,A* - Task completion to select three targets.
- *Select3,1 / Sel3,1*- Selection of the first target from a set of three.
- *Select3,2 / Sel3,2*- Selection of the second target from a set of three.
- *Select3,3 / Sel3,3*- Selection of the third target from a set of three.

- *MT*- Movement time.
- *DT*- Distance travelled.
- *VT*- Velocity taken.
- *R-HI*- Right handed interaction.
- *T-HI*- Two handed interaction.
- *L-AE*- Linear arm extension interaction technique
- *NL-AE*- Non-linear arm extension interaction technique
- *L-VBT*- Linear velocity based travel interaction technique
- *NL-VBT*- Non-linear velocity based travel interaction technique

Within Figures, different colours were used to represent a haptic force feedback condition. For the trajectory graphs, we used black or coloured dotted and solid lines to signify movements made with the left and right hand respectively:

- *Red*- No force feedback condition.
- *Blue*- Hard force feedback condition.
- *Green*- Soft force feedback condition.
- *Dotted coloured line*- movement made by the left hand.
- *Solid coloured line*- movement made by the right hand.

1.8 Thesis Structure

1. *Chapter 2, Haptic Interaction in IVEs*- This chapter presents the background research of this thesis. We provide an introduction to haptic feedback, haptic sensory-motor control, haptic physiological and their relationship to 3D interaction. We then give an overview of different haptic devices available, and the relevant HCI studies into 3D selection models.

2. *Chapter 3, Hardware Integration and Experiment Methodologies*- We describe the methods developed to integrate two large scale haptic force feedback devices within a CAVE^{TM}-like IVE. This includes calibration protocols that aligned the local coordinate frames of the connected multimodal devices to a common spatial and temporal domain. We also outline a testbed design approach used when creating the IVE experiments in chapters 4, 5 and 6.

3. *Chapter 4, Haptic Force Feedback Effects on Distal 3D Selection*- Results from user studies that evaluated the effects of haptic force feedback on two types of distal selection techniques. We start by describing the implementation of two distal 3D selection techniques and the IVE experiment

used to assess user performance. We then provide a detailed analysis of user performance, highlighting the observed changes in selection behaviour with respect to different visual and haptic combinations.

4. *Chapter 5, Haptic Force Feedback Effects on Natural 3D Selection*- We discuss the effect of three different types of haptic force feedback responses when selecting targets using a natural 3D selection technique. We define the methods used to co-locate the visual and haptic cues and implement a natural 3D selection technique. We also describe the IVE experiment and tools developed to assess user performance. Building upon work from chapter 4, we investigated both right handed and two handed modes of interaction, outlining the selection strategies used under different haptic force feedback conditions.

5. *Chapter 6, Effect of Target Size and Haptic Force Feedback on Natural 3D Selection*- We extended the user study from chapter 5 to evaluate the interaction between target size and haptic force feedback when using the natural 3D selection technique previously implemented in chapter 5. In particular, we analysed the captured results with respect to Fitts' law. From this, we outline the trade-off between haptic force feedback and task efficiency.

6. *Chapter 7, Conclusions*- Summary of the overall results presented in this thesis.

Chapter 2

Haptic Interaction in IVEs

2.1 Overview

A primary goal when designing IVEs is to create an intuitive representation of the 3D world. However, due to factors such as inadequate depth perception, poorly integrated input devices and workspace constraints, 3D interactions can be hard to perform within these environments [BRC06]. Therefore, the development of interaction techniques that enable better object selection and manipulation is important to improving the usability of IVE platforms.

From a neuroscience perspective, the exploration of 3D objects consists of both multimodal perception and intersensory integration [WW80] [WP81]. Highlighted by Chen and Srinivasan, this involves gathering information from human visual, auditory and haptic systems [BHSS00]. Whilst research investigating the visual fidelity of IVEs is well founded, comparatively little work exists on the sensation of touch.

By using haptic devices to simulate these cues, designers of novel multimodal interfaces argue the advantages of tactile and force feedback over other sensory modalities. However, as research linking haptic feedback to 3D interaction is still in its infancy, we are yet to fully explore the underlying effects on the user. Therefore, to address the main concepts of this thesis, we have segmented the background literature into four sections:

- *Haptic Interaction (section 2.2)*- Introduction to haptic feedback, outlining its role in user perception and sensory-motor control. We also discuss the haptic physiology generating these cues in the context of 3D interaction.
- *Haptic Interfaces and Design (section 2.3)*- Taxonomy of haptic devices used within virtual reality setups and their performance capabilities.
- *3D Interaction Techniques and Task Design (section 2.4)*- We discuss the different design approaches when creating 3D interaction techniques and how this translates to the types of interaction tasks users can perform within an IVE.
- *3D Selection Models and the Effects of Haptic Force Feedback (section 2.5)*- Overview of interaction models examining the relationship between user performance and haptic force feedback.

2.2 Haptic Interaction

2.2.1 Introduction to Haptics

Derived from the Greek word haptesthai, the term 'haptics' is used to describe the sensation of touch [Web90]. Experienced when using our body to interact with the surrounding environment, the perception of touch enables us to interpret the physical attributes of objects, such as their density, weight, temperature, texture, and geometric structure. Without these cues, common real world tasks become difficult to perform. For example, we would not be able to hold a glass of water if our hands are not able to sense whether they are in contact with the external surfaces [RDLT06] [Gru08] [BDE08]. Beyond real world analogies, we also use haptics to refer to the simulation of touch, in particular the physical interaction between virtual objects and the user.

Touch is defined as 'the sensation evoked when the skin is subjected to mechanical, thermal, chemical or electrical stimuli' [Sep96]. Specifically, touch describes a chain of events initiated when the body applies pressure to an object's surface or vice versa, triggering an electrical discharge from receptors located under the skin [Bur96]. When stimulated, these receptors send a set of physiological responses to our brain, which are then interpreted as information. Through this process, touch helps to build a mental image of the surrounding environment establishing a link between our body and objects. From this model we are then able to enact subsequent interactions within the presented world.

Depending on the type of receptor activated, we can perceive touch as a combination of tactile and kinesthetic cues [SC02]. For example, when our hands move lightly over a desk, the receptors under the fingertips develop a sensation illustrating the texture and temperature of the top surface. In contrast, if we were to push our hands down with greater pressure, the muscles in our wrists and forearms would start to contract, making the receptors in the ligaments and bones measure the reaction forces applied to and from the desk. Combined, these cues are synonymous with our natural understanding of touch, yet we consider them as two distinct types of information. Therefore, when describing the sense of touch, also known as haptic perception, research often discusses this separately as tactile or kinesthetic feedback.

When simulating touch within IVEs, we use specialised input devices called haptic interfaces. Depending on the type of device used, the user can experience either tactile or kinesthetic cues, or sometimes a combination of the two [ZGLSA10]. Unlike traditional 3D input devices, haptic interfaces have both input and output channels that establish a bi-directional connection to the user. These devices can also act as high-fidelity tracking instruments, providing information such as user position and orientation.

By combining haptic cues with other modes of stimuli we are able to create novel multimodal interfaces. In these types of systems, designers have the freedom to use different types of sensory cues together and describe events in a variety of ways. Depending on the level of synchronisation and coherency between each of the different input modalities, this can greatly influence the perception of the presented environment. Therefore, care must be taken when designing haptic and multimodal display systems as not to promote any detrimental effects to user performance.

When incorporating haptic interfaces within virtual reality applications, the main motivation is to improve usability. As described by Xiaoxia et al. the addition of force feedback to virtual reality simula-

Figure 2.1: Human body as a composition of perceptual receptors, joints, tendons, muscles and skin [Dav12] [Net10]

tions can enhance their realism, especially when dexterous manipulation of virtual objects is concerned [XW10] [Sta02]. Whilst methods to improve 3D interaction using novel input devices is a growing area of research, performing common real world tasks is still difficult [SP05]. Due to the extra bandwidth provided, researchers have explored the use of haptic interfaces in IVEs, demonstrating their benefit to user performance [YBB08]. However, due to the infancy of this work, our understanding of how haptic feedback influences user interaction remains unclear.

Only a small number of studies have attempted to model the effects of haptic feedback on 3D interaction. For the most part, researchers believe haptic feedback is beneficial for all situations, but through this thesis we highlight instances where this is not true. Therefore, by outlining these profiles we believe this will inform designers to create better IVEs that use haptic feedback.

2.2.2 Haptic Perception

Haptic perception is the process of recognising objects through touch. To experience this, we have a haptic system located within our body. Shown in Figure 2.1, this is a complex integration of perceptual receptors found in the joints, tendons, muscles and skin. For example, when performing an interaction task, such as reaching to touch an object, the application of force and skin pressure stimulate receptors resulting in the perception of kinesthetic and tactile cues respectively. With this information, we are then able to use active exploration techniques to identify 3D objects more efficiently.

Relating haptics to active exploration, Gibson et al. defined the haptic system as 'the sensibility of the individual to the world adjacent to his body by use of his body' [Gib66]. This definition was the first to highlight the role of touch in establishing a link between the body and its surrounding environment. In brief, Gibson stated that joints yield geometrical information, whilst the skin provides information specifying to the layout of external surfaces. By stimulating these areas and their associated receptors with force and pressure cues, the resulting sensation illustrates the bone directions of our limbs relative to the spine, head and gravity; referencing the body to the 3D space. We believe this is an important distinction, as besides interpreting the physical attributes of 3D objects, haptics also refers to the orientation of the body.

At present, there are only a few HCI studies that investigate factors associated with our motor subsystem. Research into the design of haptic devices should help, providing information about human motor capabilities, such as maximal force exertion, force tracking, force control bandwidth and others. This should also provide IVE designers with more informed choices when creating better 3D interaction techniques that incorporate haptic feedback.

2.2.3 Human Haptic System and Sensory-Motor Control

When moving to complete a task, we use our senses to interpret how best to control our limbs. As discussed, the human haptic system is a feedback mechanism through which we continually track the body and make adjustments. Humans use a combination of position and kinesthetic sensing to perform motor control as part of daily activities. Srinivasan and Chen note that in addition to the tactile and kinesthetic sensory channels, the human haptic system also includes a motor subsystem which enables control of body postures and motions [BHSS00]. Therefore, this makes contact forces one of the most important variables to consider when moving to perform actions.

As we use our hands to explore and manipulate objects, these tasks are dominated by a combination of different control loop mechanisms that infer the amount of force we exert through our muscles and onto the surrounding environment. For example, interactions that simply detect changes are thought to be passive, whilst manipulation tasks aimed at 'actively' modifying the environment are motor-dominant tasks [WU09]. Other loops also exist such as the volitional control loop utilised when maximum force exertion takes place, whereas the reflex loop minimises the applied forces to reduce physical fatigue.

Another example of how we are able to change our ability to apply force is fingertip grasping of slippery objects. Here the applied force depends on both the load being lifted and the object's surface coefficient of friction. Shown by Johansson and Westling, the rate of change in the grip force and the final grip force value increased with the degree of surface smoothness. This work found that the weight of the grasped object did not affect the force-to-load ratio required to prevent slip, but increased the duration to attain a steady-state force. Thus the grip force increased with load, but the final steady-state force for each load depended on the surface friction. A local anaesthetic was subsequently used to block tactile information from fingertip receptors. The resulting deterioration of the grip force control and induced object slippage illustrated the importance of tactile sensing during grasping [JW88] [BFJ99].

In broad terms, our ability to perform tasks relies on a complex relationship between the force applied to objects and a host of other factors such as maximum force exertion, force tracking, torque, compliance and viscosity resolution, finger mechanical impedance and force control bandwidth. For a full review see [WHF96].

2.2.4 Haptic Feedback Types and 3D Interaction

When describing different types of haptic feedback, we divide this space into two fundamental input cues: tactile and kinesthetic feedback [SC02]. Depending on the difficulty of the task, one cue can be more important than the another. For example, when feeling the surface texture of an object, this utilises taction as the dominant cue. Conversely, when determining the length of a rigid object using a pinching grasp we would predominantly use kinesthetic cues. In more complex tasks, both of these haptic cues play a fundamental role.

We do not distinctly feel different types of haptic feedback but experience them as a chain. For example, when a hand pushes very lightly against a desk the touch fingertip sensors respond first by giving the sensations associated with tactile feedback. If the hand then pushes harder the muscles in the hand and forearm start to contract. In this instance, kinesthetic sensors on muscle ligaments and bones feel the level of force now applied as opposed to the fingertips. Ultimately when describing touch, tactile sensors provide information on contact-surface geometry (the smoothness of the contact surface, its temperature etc.), whereas force feedback associated to our sense of kinesthesia gives information on the total contact force (whether a surface is hard or soft, or an objects weight). By understanding these distinctions between the stimulated physiology, this will help designers integrate haptic devices for better 3D interactions within IVEs.

2.2.5 Haptic Physiology

Tactile and kinesthetic feedback differ in several aspects such as physiology, control requirements, and functionality. We sense tactile feedback with receptors placed close to the skin, with the highest density found in the hand. Conversely, we associate kinesthetic feedback with low-bandwidth receptors placed deeper in the body, typically on muscle tendon attachments to bones and joints. Together, these receptors provide information on the total contact forces exerted, as well as grasp object compliance and weight recognition. In contrast, kinesthetic feedback has a greater influence on exploratory interaction tasks. Therefore, whilst we mention the effects of tactile feedback, a detailed analysis is beyond the scope of this thesis. For a full review see [LJ11] [Bur96] [VJE02].

2.2.5.1 Kinesthetic Feedback / Force Feedback

We associate information from kinesthetic feedback with the application of pressure or tension on receptors located in the muscles, joints and tendons. Also called force feedback, this term describes the role of force cues providing a positional awareness of our limbs when moved. Kinesthesia, defined as the perception of movement, weight and position is a key component in establishing our hand-eye coordination and muscle memory. Through this we are able detect changes in the angular position of our skeletal joints, in addition to their velocity. Studies often link force feedback with the sense of proprioception, as they both contribute to building the relationship between our body and the physical objects that surround us [BDE08]. With respect to understanding 3D interactions, this is important to assess, as these cues greatly influence our movement patterns and potential hand strategies when performing tasks.

First to describe how force affects movement, Scaliger in 1557 defined the 'sense of locomotion' to highlight how our body interprets position and motion. Much later in 1826, Bell expanded this idea creating the term 'muscle sense' to define a feedback mechanism where our brain sends commands to the muscles that then report back their condition. Later in 1880, Bastian suggested the term 'kinesthesia' instead of 'muscle sense' on the basis that some of the afferent information comes from other structures including tendons, joints and skin. Goldscheider extended this further by classifying kinesthesia into 3 types: muscle, tendon and articular sensitivity, ultimately localising this research to these specific areas of the body [Gan96].

Introducing the perception of one's own body as a whole, in 1906 Sherrington described the concepts of 'exteroception', 'interoception' and 'proprioception'. He explained, 'exteroceptors' and 'interoceptors' gave us information from outside the body such as eyes, ears, mouth and skin, and internal organs respectively; whilst proprioception is the awareness of movement derived from nerves within the body, as well as by semicircular canals of the inner ear [Bur96]. In essence, he regarded proprioception as a distinct sensory modality providing feedback solely on the status of the body internally. Through proprioception, we can understand whether the body is moving with the required effort, as well as the positional relationship of the individual body parts.

Whilst studies interchange the definitions of proprioception with kinesthesia, the latter has a greater emphasis on muscle, joint motion and force sensing. Ultimately, researchers believe that the proprioceptive sense encapsulates more than just information from the skin associated with kinesthesia and touch, but also from other sensory modalities such as audio and sight. For example, proprioception takes into account external factors such as the weight of our limbs, balance, or the appearance of an object helping to co-ordinate our body appropriately. Therefore, we regard proprioception to be a high level feedback mechanism enabling us to move more efficiently in 3D space.

2.2.5.2 Physiology of Kinesthesic Feedback / Force Feedback

Burdea et al. explained that motion of the body determines changes in pressure applied to receptors associated with free nerve endings, which in turn activates a response sent to the brain [Bur96]. In particular, compression or stretching at the joint changes the amplitude of the receptor's potential discharge, which the nervous system then subsequently interprets as position. Changes in the frequency of this discharge, such as rapid compression and extension of the receptor correspond to joint velocity. Other attributes, as such the sensitivity of joint position receptors contribute to the accuracy by which we control our limbs. This can vary depending on the area stimulated, for example, hand rotations made with the shoulder will produce a much larger positioning error than those made with the wrist. When force is applied, all these factors define the movements made by the user when performing an interaction.

Connecting the receptors together, the central nervous system integrates position information from joint sensors with data received from other sensors such as Golgi tendon organs and muscle spindles. Golgi organs are located between muscles and their corresponding tendons and play a role in triggering kinesthetic sensors. As result, they also have the function of localised tension detectors and regulate muscle co-contraction playing an important role in fine motor control.

The second type of receptors are muscle spindles located between individual fibres throughout the muscle. We stimulate muscle spindles by stretching the neighbouring muscle fibres (both passive and active). Although the Golgi tendon organs measure the muscle tension, the spindles can determine the rate of increase in the muscle length. The Golgi tendon organs and muscle spindles are mechanoreceptors that play the most important part in kinesthesia. Force sensation is also a function of muscle fatigue, which increases the perceived force magnitude, even when the force actually produced by the muscle stays constant.

Stretching of mechanoreceptors can also contribute to additional kinesthetic and proprioceptive sensing. This is true especially for receptors located in the skin covering our hands, feet and face. However, Jones and Hunter state that the precise contribution of signals arising from these areas remains unclear due to inconsistencies in present experimental results [JH92] [Gan96].

In general, kinesthetic cues can be both active and passive. Active kinesthetic cues are sensations perceived when movement is self induced, whilst passive cues indicate when our limbs are moved by an external force [Stu96]. For a full review see [BKT86].

2.3 Haptic Interfaces and Design

Haptic interfaces, also known as haptic devices, enable communication between a person and a machine through touch. Whilst we use the sense of touch when controlling common HCI devices such as a mouse, tracker ball, light pen and keyboard, these are not true haptic interfaces, as they do not provide the necessary bi-directional feedback loop through our skin and muscles. A haptic interface differs from traditional interaction devices in that they allow both ‘input’ from the user onto the virtual world, and ‘output’ from the virtual world onto the user.

The ability to render haptic feedback in a 3D application is a powerful tool. From an IVE standpoint, haptic displays can help improve the realism of a virtual environment [Sta02]. Nevertheless, providing accurate tactile and force feedback sensations can be difficult to achieve. Ultimately, a poor quality haptic device, and its integration with other sensory modalities can hinder the immersive experience. Furthermore, designers must also overcome additional limiting factors such as cumbersome mechanical architectures, latency, in addition to understanding the impact of how the user operates these unusual devices.

2.3.1 Haptic Design

The development of haptic interface designs have led to many different approaches. As work in this area progresses, so does the complexity in mechanical architectures, movement ranges and rendering. Force feedback devices are defined by their degrees of freedom (DOF). A degree of freedom refers to a direction of movement. Common degrees of freedom include right-left movement in the X axis, up-down movement in the Y axis, forwards-backwards movement in the z axis, roll around the Z axis, pitch around the X axis, and yaw around the Y axis. DOF can also refer to both how a device keeps track of position, and its output forces. A mouse, for example, is a 2 DOF input device - it keeps track of position in the right-left axis, and the forward-backward axis. A joystick is also a 2 DOF device, but the axes are different as it rotates forwards-backward, and right-left. A force feedback joystick is a 2 DOF device with force feedback. It both tracks 2 DOF and gives simple forces in 2 DOF.

To date, the application of haptic devices are divided into two branches: tele-operation and virtual reality. In tele-operation, a human operator controls a robotic device, receiving forces based on the contacts the robot is making with real objects. The challenge in this field is in detecting the contact forces without hindering the manipulation task and also in overcoming stability issues associated with network latency if the operator and robot are a long distance apart. With respect to virtual reality, this relates to accurately simulating the visual and haptic sensory channels providing an environment whereby the user can interpret these inputs in an intuitive manner and perform subsequent tasks. To do this, designers require computationally efficient models and algorithms that match human perceptual capabilities with accuracy, resolution, synchronisation and alignment. Furthermore, perceptual issues based on different types of visual and haptic mappings greatly affect the quality of the generated illusion.

Haptic interfaces have many different characteristics that describe their output. Bowman et al. state that the most common parameters are haptic presentation and capability, resolution and ergonomics [BKLP05]:

- *Haptic Presentation Capability*- This describes the type of sensory output the device renders. For example, a haptic device might provide tactile or kinesthetic cues or both.

- *Resolution*- The resolution of a haptic device is an important consideration both spatially and temporally. For example, the forearm is less sensitive to closely placed stimuli than the fingertips [SC02]. Therefore, a tactile device designed for the fingers should have much higher spatial resolution than one designed for the forearm. The temporal resolution of a haptic display refers to the refresh rate. In force feedback displays, a low temporal resolution can adversely affect quality, causing unintended vibrations and making virtual objects feel softer than intended. In many cases force feedback displays need refresh rates of up to 1000Hz to provide a suitable output.

- *Ergonomics*- As haptic displays generate forces by having a close coupling to the user, ergonomics plays a vital role in characterising their performance. Safety is an important consideration for any haptic device. For example, many tactile displays use electrical stimulation to activate tactile receptors. Care must be taken not to use too much current, or injury can result. In addition, many high-fidelity force feedback displays can exert forces that could be unsafe, and if there are errors in the haptic rendering software this could injure the user. In addition to safety issues, user comfort is another primary concern with haptic displays.

2.3.2 Examples of Large Scale Haptic Devices in IVEs

Haptic force feedback devices are available, either in laboratories or commercially, for a wide range of application areas. Most of them use a system of impedance control whilst a few adopt an admittance control methods. For general tool based applications there are the PHANToM devices developed by SensAble Technologies at MIT and the DELTA Haptic Device by Force dimension. More generally, we can categorise them as a function of force and workspace requirements. As our interest is with large

Figure 2.2: Percro GRAB haptic device

scale IVEs, we only survey a small number of devices for this scenario. For a full survey see [SB97] [PSS$^+$05].

- *Desktop Interfaces*- These are interfaces developed for desktop applications such as Virtual Sculpture or Computer Aided Design. Their intended use is with a workstation and they act as a 6 DOF mouse with force feedback. Typically the workspace for desktop devices are limited (approx. 50mm to 100mm), as well as their force capacity (approx. 5N to 10N). Show in Figure 2.3(a) and Figure 2.3(d), the most common examples of desktop haptic devices are the PHANToM Desktop made by Sensable Technologies and Novint Falcon respectively.

- *General Haptic Interfaces/High Fidelity Tele-operator*- Interfaces in this category are intended for general purpose haptics and tele-operation applications requiring high precision and sensitivity such as tele-surgery. Used with an elbow support and a stylus handle to improve precision, the typical workspace is approx. 150mm to 300mm whilst force feedback is limited to the fingers (approx. 10N to 20 N). Examples of these devices include the Quanser (Figure 2.3(b)) and Delta series by Force Dimension.

- *Scale One Interfaces/Remote Handling*- Used in workbenches or large scale environments to virtually simulate real manipulation as close as possible to 1-to-1 scale (considering displacements and forces). Operators can use these devices with one or two hands with large forces (power grasp). Forces are however limited due to technology constraints and for safety purposes (approx. 20N to 60N). They exploit movements of arm and forearm (workspace approx. 300mm to 500mm).

- *Hand Exoskeletons*- These devices enable natural finger interactions (workspace approx. 50mm to 150mm and force approx. 5N to 15N). Force is limited due to technology constraints and for

(a) PHANToM Desktop by Sensable Technologies

(b) Quanser 5 DOF Haptic device

Figure 2.3: Examples of different types of haptic devices

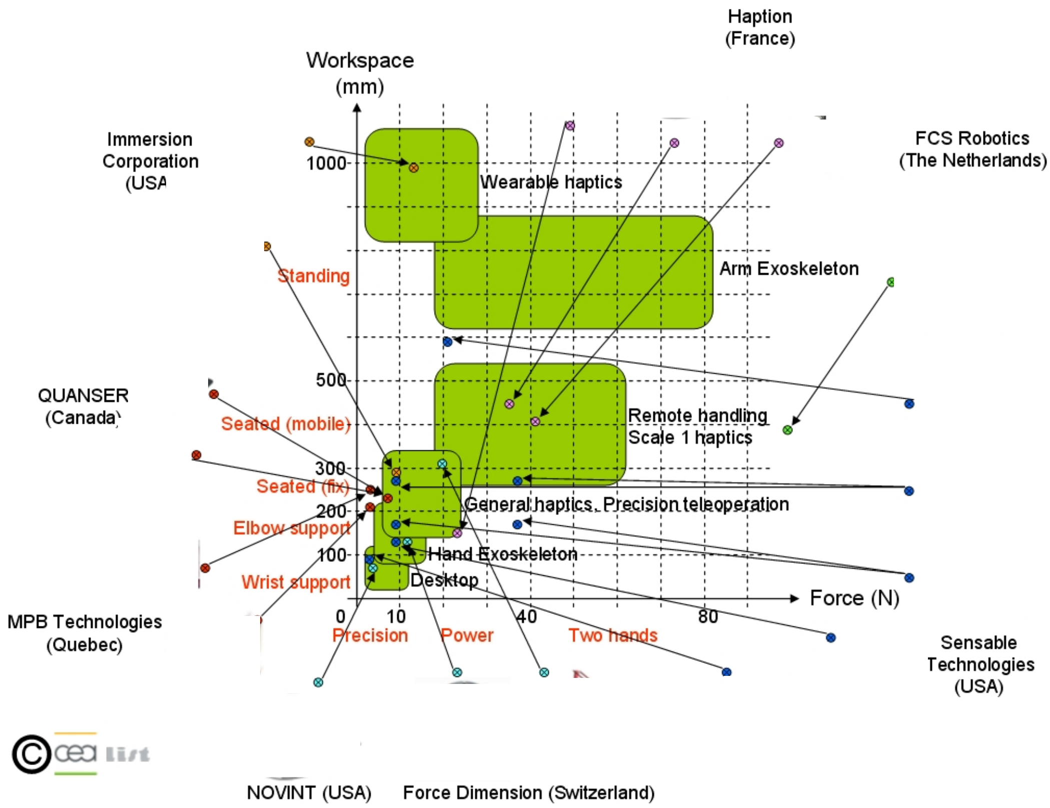


Figure 2.4: Haptic devices and their laboratories [GJBA05]

safety purposes. For simplicity, some of these interfaces like the Cybergrasp from Immersion Corporation as shown in Figure 2.3(c) allow only force on finger closure. More complete interaction can be obtained with CEA-LIST or PERCRO hand interfaces (with limitations to 2 or 3 fingers). Ease of use and adaptability to general public is of particular importance. These devices can also be mounted on other large scale haptic interfaces.

- *Arm Exoskeletons*- Similar to hand exoskeletons, these devices allow for natural hand interactions (workspace approx. 600mm to 900mm and force approx. 20 to 80N). These devices can be used for rehabilitation purposes. Again, force is limited due to technology constraints and for safety purposes. Ease of use and adaptability to general public is of particular importance. Typical examples include the PERCRO GRAB haptic interface as shown in Figure 2.2 and the HapticMaster by Moog.

Figure 2.2 is an example of the two handed PERCRO GRAB haptic device that was available to this thesis. Each device, designed for bi-manual interaction is a 6 DOF device capable of producing force feedback over 3 DOF. The user interacts with both devices using a chopstick metaphor by placing their index fingers within the provided thimble joints. By using this coupling between the user and the device, typical methods of interaction include grasping with two fingers and pointing.

To provide a general overview, Figure 2.4 compiled by CEA-LIST describes the devices developed by the different researchers laboratories and their workspace constraints [GJBA05].

2.4 3D Interactions Techniques and Task Design

3D interactions describe the user's ability to coordinate themselves in the virtual space by exchanging information with the computer systems displaying the environment. When developing suitable interaction techniques, IVE designers aim to create methods that benefit the user. As the design space of potential interaction techniques is large, current research segments this work into two problem classes: manipulation and locomotion. For an in-depth discussion on locomotion see work by Bowman et al.: [BKLP05].

To enact 3D interactions within an IVE, we track the movements of the user by using 3D input devices. Typically we use devices that calculate the position and orientation of the user's head and hands to drive the viewing perspective and virtual interaction points or cursors respectively [CH90]. To define the behaviour of these points, the developed interface translates the information from the input devices into pre-defined functions that relate to actions within the IVE. Collectively, these methods define an interaction technique whereby designers have the freedom to use a variety of mappings that determine how tasks are achieved within the virtual environment [BBM07].

As described by Hutchins et al. when using an interaction technique, the user suffers from common problems: the difficulty of forming the appropriate actions to perform a task (gulf of execution), and then understanding and evaluating the response (gulf of evaluation) [HHN85]. Due to these factors, the user can find it difficult interacting with non-intuitive input devices as there maybe some functionality available but with no immediate way to comprehend their usage. To alleviate these problems designers often use a direct manipulation model that closely links user movements to the interaction point through which actions are performed on virtual objects [PBWI96] [BBM07]. Nevertheless, due to limitations of tracking, users still have problems such as interacting with objects that are beyond arms reach. As discussed in section 4.3, to overcome these problems researchers have created novel interaction techniques such as Go-Go hand etc. that attempt to extend the physical attribute of the user [PBWI96]. However, these techniques can be very difficult to use since the user must remember how to activate the techniques enshrined in the metaphor.

To help with these designs, a common belief is that greater immersion will help with 3D interaction performance. By increasing the perceptual bandwidth through addition sensory cues such as haptic feedback, researchers think it will benefit user interaction [WH00] [OMBG00] [SWSB07a] [SH05]. However, to understand which type of haptic interface to use, we first have to establish the types of interaction tasks we wish to perform.

2.4.1 3D Manipulation and Selection Tasks

We define the effectiveness of an interaction technique by the ability of users to perform 3D interaction tasks. By nature, the output of this evaluation is heavily dependent on the application objectives. For example, the interaction techniques needed for rapid arrangement of virtual objects in a large scale IVE could be very different from small scale manipulation techniques used to handle surgical instruments in a medical simulator. Therefore, before discussing different interaction technique designs, it is important to clarify the types of tasks users wish to perform.

We define 3D manipulation as any act of handling objects with one or two hands. To reduce this scope, at this stage we are only concerned with manipulations that preserve the shape of the target object [Fol87], in addition to human motion analysis [McC70] [Mun47]. However, even this reduced definition has many parameters such as application goals, object size, object shapes, the distance from objects to the user, characteristics of the physical environment, distracters, in addition to the physical and psychological states of the user. Therefore, designing interaction techniques for every combination of these variables is not feasible. To help choose a suitable subset of all manipulation tasks, Bowman et al. outlined two basic approaches: canonical or application-specific tasks. [BKLP05].

2.4.1.1 Canonical Manipulation Tasks

Described by Mundel et al. this method of task analysis assumes that all interactions are composed of a basic set of tasks [Mun47]. Therefore, rather than develop interaction techniques for every individual manipulation task possible, we can define user interaction as a set of simple tasks. By doing so, we define interaction techniques that act as building blocks for more complex types of interactions. Users can use these 'generic' interactions techniques together for a larger percentage of 3D manipulation activities.

By taking this perspective, we consider 3D manipulation as a combination of target acquisition (selection), position and orientation tasks. Therefore, we can design the types of 3D manipulation tasks within an IVE as a set of basic subtasks:

- *Selection*- Task of acquiring or identifying a particular object from the entire set of objects available. Also called target acquisition, a real world analogy is to simply touch an object's surface with a finger [ZBM94]. To recap section 1.5, the focus of this thesis was to evaluate the user performance of different interaction techniques and haptic force feedback conditions when asked to select a set of 3D objects. Subtasks, such as changes to the 3D object's position or rotation were not considered.

- *Positioning*- Task of changing the 3D position of an object. The real world counterpart of positioning is moving an object from a starting location to a target location.

- *Rotation*- Task of changing the orientation of an object. The real world counterpart of rotation is rotating an object from a starting orientation to a target orientation.

This break down of the tasks is compatible with a well-known task analysis for 2D GUIs [FWC84] and several task analyses for virtual environments [Min95a] [BH97] [PWBI97a].

When evaluating interaction techniques using a canonical task breakdown, user performance is dependent on many variables [FWC84]. For example, in the case of selection tasks, the user manipulation strategy would differ significantly depending on the distance to the target object, the target size, the density of objects around the target, and many other factors. Some of these task variations are more prominent than others. However, these can also be standalone tasks that require specific interaction techniques. For example, object selection within and beyond arms reach are considered two distinct tasks [Min95a]. Therefore, each canonical task defines a task space that includes multiple variations of the same task defined by specific parameters (variables that influence user performance) [PWBI97a].

These parameters are then used to define a design dimension to evaluate the suitability of each interaction technique.

Throughout, our focus was towards building general models for interaction to aid the applicability of IVEs. As a result, we concentrated on a canonical approach when designing the interaction techniques used in this thesis. To further reduce the scope of this work, we evaluated interaction techniques for selection tasks only.

2.4.1.2 Application Specific Tasks

The canonical tasks approach simplifies 3D manipulation tasks into their most essential properties. However, due to this simplification, extending these types of interaction technique designs may become difficult. For example, when positioning a virtual object to a known orientation, it is often more efficient to implement a snapping tool using an application specific interaction technique feature. Other application specific interaction techniques also include moving the control stick of a virtual airplane in a flight simulation [Mue95]. In these examples, generalisations of the manipulation tasks do not make sense. When using an application specific design approach, it is the details of the manipulation task that are important to capture and replicate.

2.4.2 Implementing 3D Selection Techniques

At an implementation level, two main classes of selection techniques exist: ray selection and volume selection. Ray selection involves a ray being cast from one of the user's limbs into the IVE without scaling the viewing perspective. However, whilst this is easy to build, these types of interaction techniques are less natural to use, in particular, when selecting objects at a distance. For example, difficulties occur when selecting small objects that are far away as limb instability and tracker jitter adversely affects user performance over these distances. Typically, the projection of the ray used comes from the hand or other parts of the body such as the head, eyes or a combination of these including bi-manual gestures [GB04]. We can even control the ray indirectly using a scaling mechanism [FK05] or other variations such as image plane interaction techniques [PFC+97].

As an alternative, volume selection techniques include examples such as virtual hand and cone selection. Volume selection can be broken down into two classes: small volume and extended volume. Small volume interaction techniques use a small workspace within the hand or surrounding the hand [MBS97]. Users can select an object when their volume intersects the target's surface. Variations of this technique change the way in which the user can position the small volume in order to get over the problem of being able to only select within arm's reach. The Go-Go interaction technique extends the virtual hand technique to support selection at a distance. Defined by Poupyrev et al. Go-Go hand is a superset of the virtual hand and that whenever the virtual hand is used, Go-Go selection is a natural and flexible extension [PBWI96].

Extended volume selection techniques use a volume projection in to the world where we select objects lying inside this space. Cone or flashlight selection is a typical technique [LG94]. In some ways it is more similar to ray selection because it is the volume direction that needs to be controlled by the user rather than the position. Some consider this to be preferable to ray selection because it is more

- *Feedback*
  - Graphical
  - Force/tactile
  - Audio
  - Text
- *Indication of object*
  - Touching
    - 1-to-1 movement
    - Position maps to position
    - Position maps to velocity
    - Velocity maps to position
    - Position maps to acceleration
    - Indirect control
  - Occlusion
  - Pointing
    - 2D
    - 3D hand
    - 3D gaze
  - Indirect selection
    - List
    - Voice
    - Automatic
    - Iconic objects
- *Indication to select*
  - Gesture
  - Event
  - Voice
  - No explicit

Figure 2.5: Taxonomy of different 3D selection techniques

tolerant of jitter and small errors. Variations include aperture based selection [FHZ96] and shadow cone selection [SP05].

A significant problem in designing interaction techniques suitable for IVEs is the wide variety of methods and user preferences [BGH02] [BH99] [SP05] [WLGP04]. Whilst this is beyond the scope of this thesis, we give a general review of current interaction techniques applicable for 3D interactions in section 4.3. For a full review of 3D interaction techniques see [Han97] and [Min95a].

2.4.3 3D Selection Taxonomies

To encapsulate the design possibilities of different selection techniques, a number of authors have attempted to build set of taxonomies. Outlined by Bowman et al., 3D selection technique design comprises of three components: feedback, indication of object and indication to select [BH97] [BKLP05].

Described in Figure 2.5, a variety of options can be used to define a 3D selection technique [Ste06] [BH97] [BKLP05]. For example, input information cues such as position, velocity and acceleration of the devices can be defined in many more ways than listed. Also, other considerations include the use of any limb or combinations of limbs to point. Nevertheless, these taxonomies are useful in highlighting the different combinations of feedback, indication of object and indication to select to consider. Ultimately, these design choices will depend on the input and output devices used and the task at hand. A natural extension to this work includes outlining the end effects of these actions in terms of user performance and usability.

2.5 3D Selection Models and the Effects of Haptic Force Feedback

Modelling 3D selection has received a lot of attention from the research community. In contrast, understanding the effects of haptic force feedback cues on 3D selection remains limited. Due to their expense, most studies use small scale haptic interfaces such as the PHANToM device. Wall et al. investigated if the addition of haptic force feedback, gravity wells and stereo graphics benefited the selection of 3D objects [WPS+02]. They showed that haptic force feedback improved accuracy, but not performance time, while stereo graphics helped both significantly. Magnusson et al. also used a PHANToM in a memory game showing that conditions with force feedback had the best results [RGME07].

Research suggests that the extra bandwidth provided by haptic force feedback cue will benefit user interaction. Starting from an information theory perspective such as Fitts' law, researchers argue that the addition of haptic force feedback will deliver more information to the user, and at a greater frequency [Fit54]. For example, as the latency of the haptic sensory loop is much less than visual cues, users will receive information from their surroundings fractionally earlier, helping their ability to perform tasks [WH00] [OMBG00]. However, from a mechanical point of view, haptic force feedback would also require users to put in more work; either pushing through virtual objects that provide resistance, or taking longer paths to task completion by avoiding obstacles that reflect a physical response when selected. As a result, we believe when displaying haptic force feedback there is also a trade-off in task efficiency which is currently not recognised.

2.5.1 Common Selection Models

One of the more successful quantitative models in HCI, is Fitts' law [Fit54]. Used to model pointing tasks, it defines the movement time (MT) to select a target of width (W) and distance, or amplitude (A), from the cursor:

$$MT = a + b \log_2(\frac{A}{W} + 1) \tag{2.1}$$

Where a and b are empirically determined constants. The logarithm term is called the index of difficulty (ID) of the task.

Despite the success of Fitts' law [Mac92], there are fundamental problems with its design. As it only addresses one type of movement, it is inherently one-dimensional. Therefore, this type of model is not adequate in describing today's set of input devices which often produce trajectory based movements

[AZ97]. Researchers have attempted to extend Fitts' law to handle pointing tasks with bi-variate targets [AZ03] [GKB07]. However these models have known limitations. For a full account of problems associated with bi-variate pointing see [AZ03] [HS94] [MW92]. This is also true for research relating to tri-variate pointing tasks [MI01] [GB04].

When evaluating Fitts' law, most studies investigate the effects of varying height, width and movement angle on MT [AZ03] [HS94] [MW92]. In comparison, little work of this type exists for the 3D domain [MI01] [PS09]. Ware et al. attempted to extend the ID_{min} model for 3D reaching tasks [WB94] [WL97]. However, its application was only in the context of investigating factors such as lag and frame rate, rather than the underlying human behaviour [Zha95]. More relevant studies by Grossman and Balakrishnan incorporate size and the movement angle within weighted functions for each dimension of movement [GB04]:

$$ID_{WtEuc\Theta} = \log_2(\sqrt{f_w(\Theta)(\frac{A}{W})^2 + f_H(\Theta)(\frac{A}{H})^2 + f_D(\Theta)(\frac{A}{D})^2 + 1})) \tag{2.2}$$

Where $f_W(\Theta), f_H(\Theta), f_D(\Theta)$ are the weighted constants for each axis of movement. W, H and D are the target's dimensions- width, height and depth respectively. A is the distance or amplitude to the target and Θ is the movement angle from the starting position to the centre of the target.

Whilst producing good correlations to the collected data, these studies are often based on using input devices that do not necessarily facilitate natural forms of interaction. By using large scale haptic force feedback devices, users are able to select objects using gestures similar to real world pointing [PS09].

Of the human factor studies that are relevant, only a few measure the performance of haptic force feedback itself. Wall and Harwin [WH00] employed a tapping test [OMBG00] to establish a measure of human performance for simple selection tasks. They showed that force feedback significantly reduced MT. The most common scenario used to compare the performance of haptic devices are 3D peg-in-hole tests and rendering of hard virtual surfaces. For a full review of haptic rendering systems see [SWSB07a] [RME$^+$06].

Studies within the Neuroscience domain have also attempted to model motor control tasks such as 3D pointing. As discussed by Shadmehr and Mussa-Ivaldi, their aim was to investigate how the central nervous system (CNS) learns to control movements in different dynamic conditions, and how this learned behaviour is represented [SMi94]. In particular, they considered reaching movements with forces externally imposed using a robot manipulandum. The results showed that since the force applied significantly changed the dynamics of the task, the initial movements of the user were grossly distorted compared to their movements in free space. However, with practice, hand trajectories in the force field converged to a path very similar to that observed in free space. This recovery of performance was called motor adaptation. Work by Burdet et al. also indicated that to manipulate objects or to use tools, we must compensate for any forces arising from interaction with the physical environment. Recent studies indicate that this compensation is achieved by learning an internal model of the dynamics, that is, a neural representation of the relation between motor command and movement [BOF$^+$01]. Their results show that humans learn to stabilise unstable dynamics using the skilful and energy efficient strategy of selective control of impedance geometry. Other works worth reviewing are studies investigating the relationship between brain and goal-directed movement behaviour in humans [Jea90].

2.5.2 Haptic Force Feedback and 3D Interaction Performance

Recent studies have considered the use of tactile and force feedback to aid human computer interaction. Prior to the widespread availability of force feedback devices, researchers experimented with augmenting the standard mouse with mixed results [ASH93]. Several research studies have investigated the effect of haptics and stereovision on systems that use a semi silvered mirror. Wall and Harwin showed that use of force feedback with a 2D graphical display of a 3D environment can improve performance in a Fitts' law style tapping test [WH00]. Similarly, Arsenault and Ware adopted a reciprocal tapping test in order to investigate the effect of haptic cues with a co-located head tracked stereo display [AW00a]. The effects of providing force feedback and head tracking were highly significant in reducing target acquisition times. Force feedback also reduced the number of errors that subjects made, and therefore gave an even greater increase in task performance. Both studies from Wall and Harwin and Arsenault and Ware, commented on the effect of force feedback allowing the user to 'bounce' between the targets during tapping tests, which facilitated faster selection times. Other studies include, Ernst et al. that demonstrated a benefit of haptic feedback in the perception of surface orientation via texture [EBB00]. Ware and Rose investigated the task of object rotation in a virtual environment with reference to a variety of factors [WR99]. Among their findings was that displacement of the visual representation of a real object (held in one hand) by 60cm led to a 35 percent slowdown in task completion time. One study showed that the effect of haptic force feedback shortened task completion times when the task was to put a peg in a hole simulating assembly work [GSW97].

In terms of combining haptic sensory cues according to strict 1-to-1 mappings with the visual cues, Ware and Rose noted that co-location of the hand and virtual workspace improved performance in tasks involving object rotation [WR99]. Studies by Graham and Mackenzie also added to this body of work, however it should be noted that these experiments were 2D and presented no visual information regarding height. Another possible problem for co-located displays is the effect of visual and haptic mismatch and inaccuracies due to poor calibration. However, several studies have shown that adaptation to small lateral displacements in this type of mismatch is rapid and of little consequence to performance. Bouguila et al. presented results that suggest that haptic feedback can help overcome instabilities in the users depth perception [BIS00]. This has obvious implications for task performance and selecting objects.

With respect to examples where researchers have used haptics in an assistive context, the most successful augmentation was in the form gravity wells that attracted the user to targets. Wall et al. investigated whether the addition of haptic feedback, gravity wells and stereo graphics would improve selection of objects in 3D [WPS+02]. The haptic feedback did improve the accuracy, but not the performance time, while stereo graphics improved both significantly. Magnusson et al. also used a PHANToM in a memory game showing that gravity wells were among the conditions with the best results [RGME07]. Most other studies into assistive force feedback cues are from the literature on 2D interaction. These studies suggest that force feedback cues implemented as gravity wells lead to 20-50 percent improvements in completion time in a selection task [HKL+01]. Other guiding examples such as haptic steering improve movement times by 52 percent [DMH00]. Navigational tools have also been tested, such as ‘magnets’ and ‘crosses’ as well as force feedback cues to help with object rotations [DPL07]. These studies show that the use of attractive cues is helpful in many circumstances, at least for 2D techniques. For 3D interaction techniques, research remains underdeveloped.

Based upon the above literature, and explained in more detail in section 3.4.3, we evaluated 3D selection performance in terms of:

- *Movement Time (MT)*- the time taken to complete the task once the user when his/her first movement away from their starting position.
- *Distance Travelled (DT)*- the size of the path taken by the user to complete the task from his/her starting position.
- *Velocity Taken (VT)*- the velocity taken to complete the task based upon results DT / MT.

Naturally, we expect the measures to be correlated, since MT must have a strong relationship to the DT and VT. For a more in depth analysis of these results, we also plotted the trajectories taken by the user, in addition to the changes in velocity to task completion (introduced in chapters 5 and 6).

2.6 Summary

In this chapter we introduced the main research areas relevant for this thesis. In particular, we have outlined the previous work from haptic force feedback and its sensory-motor control components, to 3D interaction. By doing so, we demonstrated the current challenges facing this research area, and the difficulties in integrating haptic devices to evaluate 3D interaction performance. We also highlight the contradictions between different studies investigating the effects of haptic force feedback on 3D interaction performance. As a result, the literature suggests that 3D interaction is much more complex than previously thought and is therefore worth investigating.

Chapter 3

Hardware Integration and Experiment Methodologies

3.1 Overview

We created a hardware setup to capture the user performance of a variety of 3D selection techniques. To highlight the challenges faced, we explicitly outline the technical specifications of the available equipment and their impact on the design strategies used in this thesis. We also describe a testbed approach which provided an evaluation framework as a basis for the developed IVE experiments.

In this chapter, we present the methods used to align the visual and haptic cues to a common domain. We also outline a set of calibration protocols developed to improve the accuracy and stable rendering of the connected display devices describing the IVE experiments. Finally, we discuss the design considerations made when creating the distal and natural 3D selection techniques evaluated in this thesis, in addition to the evaluation framework used to assess our hypotheses.

Throughout, we ran pilot studies with expert users to assess the suitability of our proposed solutions. Highlighted in section 2.3, few studies exist with transferable design guidelines for the available hardware. Consequently, we used an iterative process to learn from each phase of development. To describe these stages, we segmented this chapter into 3 sections (for descriptions of the IVE experiments and 3D selection techniques created refer to chapters 4, 5 and 6):

- *Hardware Specifications (section 3.2)*- Presentation of the individual hardware components and their technical specifications
- *Hardware Setup and Integration (section 3.3)*- We outline the methods developed to register the visual and haptic display devices and solutions to improve their stability.
- *Experiment Methodologies (section 3.4)*- Discuss the guidelines used to evaluate user performance.

3.2 Hardware Specifications

In total, we connected two rendering systems: a CAVE^{TM}-like projection system called the ReaCToR (section 3.2.1) and a GRAB haptic interface (section 3.2.2). Throughout the design process, we placed emphasis on the accurate and stable registration of the generated visual and haptic cues. By doing so, we wanted to limit the effects of any distracting factors which could interfere with our assessment of selection performance [HA96]. Therefore, we chose hardware dedicated to displaying at high refresh rates, ensuring the correct synchronisation for perceptual consistency [BAA+96]. Furthermore, to help coordinate the outputs from the GRAB haptic devices and the ReaCToR projection unit, we used the XVR visualisation platform (section 3.3.1).

When integrating the connected visual and haptic display devices, we registered their local coordinate frames to a common spatial and temporal domain (section 3.3.3). With this implementation, we programmed the position and movement of the 3D haptic contacts to different types of mappings. As discussed further in chapters 4 and 5, this level of integration gave us the flexibility to design both distal (section 4.2) and natural selection techniques (section 5.2) for the same visual and haptic equipment.

To further reduce any detrimental effects of the hardware setup on user interaction, we chose devices that did not restrict hand movements. Consequently, users were able to perform ballistic movements throughout their arms reach, freely and with little impedance. In comparison to other setups, integration of a large scale GRAB haptic device to a CAVE^{TM}-like IVE is a novel configuration. As result, the findings from similar work within the research domain are not directly transferable. Therefore, to understand the characteristics of the hardware setup, we first assessed the display performance (section 3.3.4). From this, we then tailored the evaluation framework to compensate for these potential errors.

3.2.1 Visual Input Device- UCL ReaCToR

We rendered the visual cues of our IVE experiments using the UCL ReaCToR, which is a CAVE^{TM}-like [CNSD+92] display system. Installed by Trimension, the UCL ReaCToR consisted of three 3m x 2.2m walls and a 3m x 3m floor. Shown in Figure 3.1, the 4 projection surfaces; the front, left and right walls are stereo projected from the back on to acrylic screens, with a painted wooden floor projected from above. In particular, the screens were seamlessly joined to provide a continuous projection surface. Only the top and the rear faces of the cube were not projection surfaces.

We generated the visuals using a custom-built PC cluster consisting of a master node with 2GB RAM and dual 1.8GHz Intel processors, and four slave nodes with 1GB RAM, single 2.7GHz Intel processors and GeForce Quadro 5600 graphics cards. All cluster nodes ran Windows XP with a pixel resolution of 1024 x 768.

To view the IVE, the user wore a pair of active CrystalEyes stereo glasses. We controlled the glasses using infrared signals synchronised with the display refresh rate. Furthermore, we also tracked its position and orientation by using an Intersense IS900 system (section 3.2.3). With this, we could dynamically change the viewpoint of the IVE in relation to the user's position and head rotation by performing low-latency precision head tracking. This allowed distortion-free and lag-free movement calibrated to the dimensions of the surrounding walls.

3.2.2 Haptic Input Device- GRAB Haptic Interface

We chose a haptic device that enabled free 3D spatial movements within a large workspace. Discussed in section 2.2.4, haptic feedback consists of three types of sensory inputs: force feedback, tactile feedback

(a) CAD drawing of ReaCToR layout

(b) Typical usage

Figure 3.1: Schematics and layout of the UCL ReaCToR visual display system

(a) Percro GRAB haptic interface

(b) Typical usage

Figure 3.2: Percro GRAB haptic interface and its typical usage

and proprioceptive feedback. As our interest was in the ballistic movements needed to perform a 3D selection, we did not consider the effects from tactile feedback [Web78], [Gib66], [SF82]. Therefore, we chose a haptic interface that rendered force feedback only (for a full review of haptic interfaces see [Sta02], [SBM+95], [HACH+04]).

For our experiments, we used a GRAB interface developed by PERCRO [AMA+03]. Shown in Figure 3.2, this device consisted of two mechanical arms with large workspaces that when combined enabled two handed interaction. In this arrangement, users could perform actions such as scaling and modelling to select and manipulate virtual objects via two 3D haptic contact points for each hand rendered in the IVE. For example, as shown in Figure 3.2(b), when using the GRAB arms, users were able to feel the physical properties, contours and extrinsic shape of virtual objects, within and throughout arms reach. Furthermore, with the ability to reflect large force vectors, we could also simulate objects

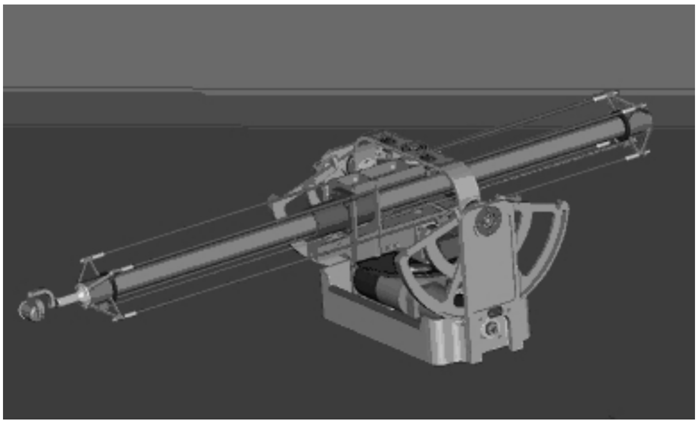


Figure 3.3: Precro GRAB haptic interface CAD drawing

with different types of hardness and inertia.

To use the device, we placed both GRAB arms at pre-defined positions within the workspace of the ReaCToR. Shown in Figure 3.2, users put both index fingers in the two thimbles positioned at the end of each arm. When in this position, the GRAB interface offered 6 DOFs where 3 DOFs had active force feedback and the rest passive. The device, with its internal sensors, tracked the position of each hand and sent this data to the XVR visualisation package for representation within the IVE. Additionally, we placed VICON markers on the device to register the 3D haptic contact points to known displacements relative to the physical position of the GRAB interface within the IVE (section 3.3.3.2).

Corresponding to typical movements made within a user's arms reach, the cubic workplace of the GRAB haptic interface was approximately 600mm (depth) x 400mm (width) x400mm (height). In reality the workspace was cone shaped extending from the centre of the base of the haptic device. Due to these constraints, the workspace was predominately located in front of the user suitable for forward based interactions.

With respect to the mechanical design, the two haptic arms were identical robotic devices each having a serial kinematics [DAM+03]. By having a total of 6 DOFs, the first 3 DOFs were active and the rest were passive. For the first 3 DOFs, the device had 2 orthogonal rotational pairs followed by a prismatic pair. Shown in Figure 3.3, these were actuated and had sensors allowing the user to experience an independent force vector and arbitrary orientation for the fingertip. For the remaining 3 DOFs these did not give any feedback or evaluation of position. By using this mechanism, we could afford gestures similar to pointing and poking.

In comparison to other solutions, the GRAB haptic interface delivered a very high degree of isotropy. This was an important characteristic, giving uniform use of the actuators and reflecting inertia in the workspace with minimal interference. Furthermore, unlike other devices, the GRAB arms offered movement with high transparency. This helped to limit the impact of the devices inertia on the user, enabling unimpeded movement within the workspace.

As outlined by Dettori et al. the full technical details for the GRAB arms are summarised below [DAM+03]. By understanding these characteristics summarised in Table 3.1 we were able to tailor the

Table 3.1: Mechanical and force feedback characteristics of the GRAB haptic device

Mechanical characteristics	
Inertia:	Low mass amongst the moving parts resulting in low perceived inertia
Stiffness:	High stiffness of the structure. Worst case greater than 5N/m
Friction:	Low mechanical friction of 20mN and 200mN with active weight compensation
Bandwidth:	High bandwidth force feedback
Dimensions:	400mm (X), 400mm (Y), 600mm (Z) - left handed coordinate system
Force Feedback characteristics	
Peak Force Range (FP):	$0 < \|F\| < FP = 40N$.
	Forces (F) exerted for a limited period of time ($<$ 1 minute)
Continuous Force Range (FC):	$0 < \|F\| < FC = 4N$.
	Forces exerted for longer period of time ($>$ 1 minute). This limitation was due to the heat dissipation of the electric motors

design of our IVE experiments and selection techniques.

3.2.3 Tracking Devices

To register the local coordinate frames of the GRAB haptic interface and the projection unit, we used two types of tracking equipment: Intersense IS-900 for head tracking and VICON motion capture system to track the haptic device. By using these systems, we captured the head position and orientation of the user, in addition to the position of GRAB arms relative to the ReaCToR walls. With this data, we compared both of these outputs to a reference frame defined by the XVR platform. By using specified position and time offsets, we used this platform to align the local haptic and visual coordinate frames to a common spatial and temporal domain.

At present, the exact level of accuracy required for visual and haptic coherence is unknown. Attempts within neuroscience have tried to model the potential disparities between visual and haptic cues when estimating surrounding objects [BGB10]. In comparison, there are only a few studies within HCI and other engineering disciplines that investigate variations in visual-haptic alignment on user interaction performance. Therefore, to limit the effect of these potential factors, especially when simulating methods for natural interaction, we assumed the need for a high level of accuracy and correspondence between the displayed sensory cues.

3.2.3.1 Head tracking- Intersense IS-900

For natural viewing of the 3D environment, we linked the viewing perspective of the virtual environment to the head position and orientation of the user. To do this, we used the IS-900 tracking system. This provided accurate and smooth movements with low latency, enabling real-time interaction updates between the user and the 3D environment. Shown in Figure 3.4, by placing the Intersense sensor on the active stereo glasses, we captured the real-time position and rotation of the user's viewing frustum. From these values, we updated the viewing perspective within the XVR visualisation platform and projection units accordingly.

The sensor consisted of sonic and inertia tracking components used to compute a 3D position and

Figure 3.4: IS-900, Head tracking sensor on stereo glasses and sensor bars

orientation vector. Connected to the IS-900 control box, these components communicated with sensor bars placed at the circumference of the ReaCToR walls. By calibrating these bars to the dimensions of the ReaCToR, we outputted 3D orientation and position values relative to the surrounding walls in metres. With these values, the control box then streamed the position and orientation vectors via UDP to the visualisation cluster node to then update the virtual scene. We achieved this at 180Hz to give a high refresh rate and limit any perceived perspective distortions.

To outline the accuracy specifications, we have summarised the technical data below [PKS+08]:

- *Degrees of Freedom*- 6 DOF (X,Y,Z, Yaw, Pitch, and Roll).
- *Angular Range*- Full $360\,^\circ$ (all axes).
- *Resolution*- 0.75 mm, $0.05\,^\circ$.
- *Static Accuracy*- 2.0-3.0 mm, $0.25\,^\circ$ RMS in Pitch & Roll, $0.50\,^\circ$ RMS in Yaw.
- *Update Rate*- 180 Hz.
- *Latency*- Approx. 4 ms.

To assess the registration quality, we evaluated the accuracy of IS-900 throughout the movement space of the ReaCToR. Discussed in sections 3.3.3.1 and 3.3.4, and in line with findings from Gilson et al., we found that whilst position was accurate, movements in head rotation caused 'drifting' errors [GFG06]. To compensate for this potentially distracting factor, we designed 3D selection techniques that did not involve large head rotations around the z and y axes. To note, we did not track the eye position of the users. As a result, we did not account for changes in viewing perspective with respect to these movements in addition to differences in eye separation.

3.2.3.2 Tracking of GRAB Haptic Interface- VICON

To register the coordinate frame of the GRAB arms to the spatial domain of the XVR platform, we needed to find its 3D physical position within the ReaCToR space. Due to the unusual shape of the haptic device, we placed reflective VICON markers on the base in a set pattern shown in Figure 3.5. By using motion tracking cameras placed around the circumference of the ReaCToR, we programmed the VICON IQ/MX software platform to recognise a pre-defined marker pattern for each arm. By using its

(a) Close up of GRAB haptic interface with VICON markers

(b) Both GRAB arms with VICON markers

Figure 3.5: Percro GRAB haptic interface with VICON markers

real-time engine, we captured an accurate 3D position and orientation vector of this model relative to the dimensions of the ReaCToR to then update the XVR visualisation platform accordingly. We discuss the developed calibration protocols in section 3.3.3.

Potentially more accurate than the IS-900, we found that the optimal running requirements of the VICON system was heavily dependent on the initial system calibration. Based upon our performance evaluation in section 3.3.4, this involved identifying both internal and external camera parameters. Once established through a set routine as described in section 3.3.3.1, we used these values to reference the VICON coordinate frame with the XVR platform via a UDP connection. With this, we used the captured 3D orientation vector for the GRAB arms to then reliably reposition the 3D haptic contact points.

3.3 Hardware Setup and Integration

To define the characteristics of our setup, in this section we describe the calibration methods developed for visual and haptic alignment. For completeness, we examined the performance of the hardware used, highlighting potential design considerations and the technical challenges faced. To do this, we discuss: the architecture used to connect the visual and haptic display devices (section 3.3.1), methods developed to maintain visual-haptic coherence (section 3.3.2), calibration procedures used to align the visual, haptic and tracking devices to a common domain (section 3.3.3) and the performance of the overall system and its constraints (section 3.3.4).

3.3.1 Display of Visual-Haptic Input Cues

To control the rendering of both visual and haptic content, we used the XVR visualisation platform. Configured specifically to the characteristics of the ReaCToR, head tracking system and GRAB interface, this platform offered rapid prototyping for multimodal IVEs [RFB$^+$06]. By using the integrated PhyX engine, we defined 3D objects with physical properties allowing for dynamic interactions in real-time. Through this, the physics engine also computed a reliable force vector compatible with the GRAB arms, initiating physical force feedback cues on the user when the 3D haptic contact points collided with other virtual objects (for full details of the collision detection algorithms see [RFB$^+$06]). Described in Figure 3.6, the XVR platform coordinated and synchronised all outputs from the connected display devices.

As all the projection units and head tracking system were previously calibrated to the XVR platform and dimensions of the ReaCToR using pre-defined configuration files, we already had a reference frame accurately aligned to the volume space defined in metres. Therefore, most of our work focused on aligning the local coordinate frame of the haptic arms to the XVR reference frame by defining a suitable calibration procedure that we ran before each experiment.

Described in more detail in section 3.3.3, we firstly captured the position of the arms relative to the ReaCToR space by placing VICON markers around the thimble joint and base of the haptic arms. By using an array of infra-red VICON cameras placed at ceiling level around the ReaCToR, the VICON IQ/MX software and its real-time engine computed accurate 3D positions of these markers in relation to the circumference of the surrounding walls. This information was then sent to the XVR platform via a UDP connection synchronised to the visual update frequency, giving a 3D point representative to the

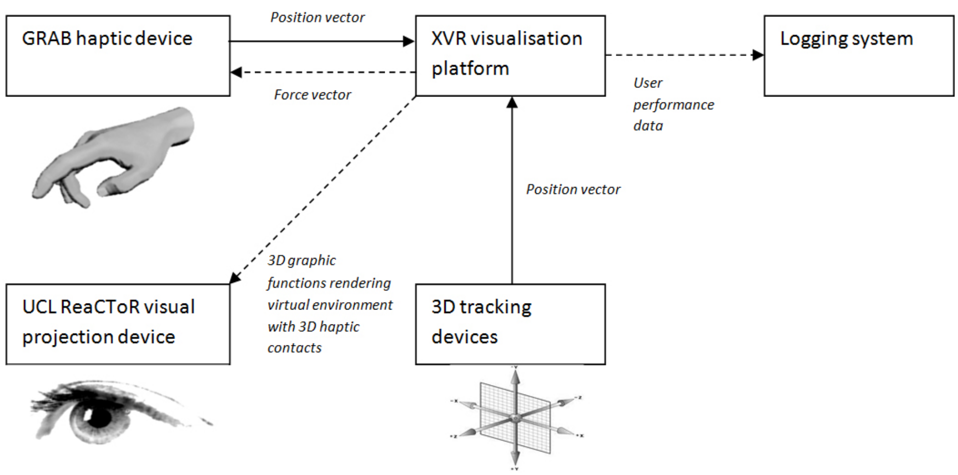


Figure 3.6: Network diagram of connected systems to XVR

physical position of the GRAB arms within the ReaCToR. We then used this point to define the position of the 3D haptic contact points for each arm by applying a pre-defined offset vector appropriate for the implemented selection technique.

Once calibrated, the position of the 3D haptic points were updated using the internal readings of the haptic arms. This information was also used within the collision detection algorithms to detect intersections between the haptic points and virtual objects within the scene to then apply a force. Upon contact, the physic engine within XVR computed and sent a suitable force vector for safe application on the GRAB arms. To compensate for physical movements of the GRAB devices due to accidental knocks, we also implemented a function to regularly check the position of the 3D haptic points and its pre-defined offset relationship for major differences to then halt the simulation.

To assess the accuracy of the local coordinate frame of the GRAB interface to the global domain, we again constructed a calibration procedure to establish the correct alignment. Discussed in section 3.3.3.2 this involved compensating for errors with the internal trackers. As we used these trackers to update the repositioning the 3D haptic contact points during the interaction process, we performed a set of pilot studies to identify any distortions. For a 1-to-1 mapping with the global domain, we used a 1.02, 0.88 and 1.0 multiplication mapping for each of the x, y and z DOFs for both GRAB haptic arms respectively.

Through this setup, we achieved an environment whereby the 3D haptic contact points were controlled directly by input movements made by the user's hands. Defined as two grey spheres, we mapped the movements of the user's hands directly into the IVE and generate a force made by the haptic interface. By using the XVR platform to coordinate the exchange of information between devices, we were able to script different types of interaction designs based upon the input data from the 3D trackers and haptic interface. Discussed in chapters 4 and 5, we developed different types of distal and natural selection techniques respectively. We also created a system to output a set of log files for each of the connected devices describing the user's performance within a multimodal environment (section 3.4.3).

3.3.2 Maintaining Visual-Haptic Coherence

Multimodal environments share a common problem of coherence. Whenever the interaction between the user and the system uses several afferent sensory channels, it requires that all input cues must have synchronisation with respect to time, force and space [HA96]. As highlighted by Bergamasco et al. the lack of synchronisation in one or more of these afferent channels can result in degradation in the user perception of the IVE, such as a lack presence up to a sense of sickness during the virtual interoperation [BAA+96]. Due to these potential problems, we evaluated our hardware setup for accurate calibration of the generated visual and haptic cues.

To reduce the effect of perceptual breaks on the underlying user performance, we first assessed the spatial accuracy of the projection units in addition to the tracking systems. As outlined by Brown et al., images from a multi-projector display must appear seamless, as if projected from a single display device [BMY05]. By running a set of pilot studies on the visual display unit, we used the manufacturers calibration utilities to define a set of tailored configuration files, adjusting for geometric misalignment and colour variations within and across the different projectors that created the final image. This was also true for updates to the viewing perspective controlled by the IS-900, which needed to change in a consistent manner with respect to actions made by the user recorded by the tracking system. By accounting for these integration problems, we achieved a display quality that was both geometrically and photo-metrically accurate.

With respect to geometric registration, we wanted continuity within the workspace of the GRAB arms when using different interaction alignments. For example, when using a natural interaction technique we wanted a 1-to-1 mapping whereby a 10cm movement of the haptic arms resulted in 10cm movement of the 3D haptic contact points in the IVE accordingly. Furthermore, we wanted to ensure the stability of the projection model as the user moved and rotated their head. To do this, we reduced any 'drifting' effects and inaccuracies between the tracking and projection systems with a set of tailored calibration files.

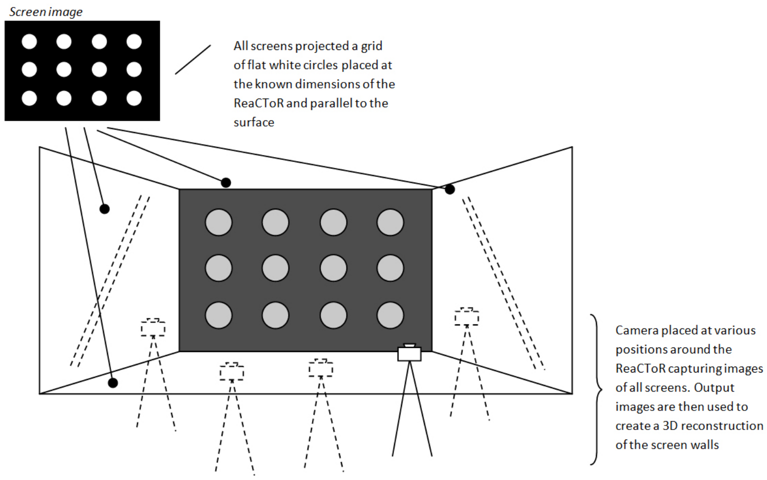
As discussed by Yang et al., there are different approaches to achieving accurate calibration. The most common approaches couple mechanical and electronic equipment to then check for alignment disparities [YGH+01]. However, this can be expensive. Furthermore, these methods do not correct for non-linear distortions like projector radial and intensity distortions [CNSD+92], [BSM06], [OD03]. Therefore, to calibrate a four-projector system, such as the ReaCToR can be time consuming. As a result, we used a camera based approach.

Building an automated process for geometric registration was beyond the scope of work. Therefore, the procedures implemented in section 3.3.3 are specific to the hardware used. For an evaluation of its performance see section 3.3.4.

3.3.3 Calibration Procedures

3.3.3.1 Visual 3D Geometric and Tracking Calibration

To calibrate the geometric inaccuracies of the ReaCToR, we used a camera-based approach to compensate for any distortions with the projectors. Shown in Figure 3.7, we rendered a large population of



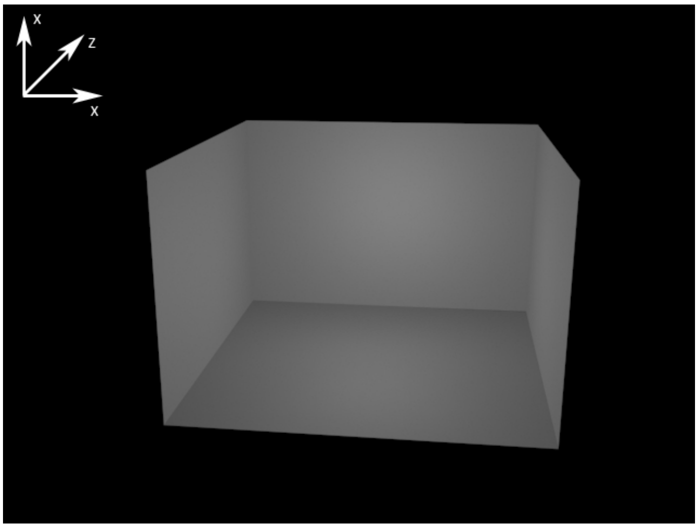
(a) 3D projection reconstruction procedure

(b) Measuring head tracking alignment accuracy

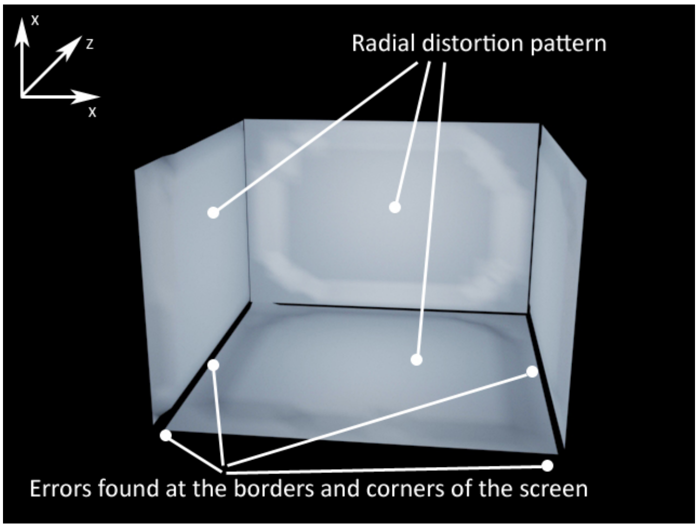
Figure 3.7: Projection and head tracking estimate calibration procedure

circles with a set size onto the known surface positions and dimensions of the ReaCToR walls. Then by using computer vision techniques, we then computed a 3D estimate of the size of the ReaCToR by taking a series of pictures from different locations whilst maintaining a static viewing perspective at the centre. By matching the known size of the circles to the captured data (compensating for the intrinsic values of the input camera and the projection resolution quality), we were able to reconstruct a shape estimate of the ReaCToR to then compare with its known dimensions.

Figure 3.8 shows the estimate produced. The projection system suffers from a radial distortion, producing good results at the centre of the screen with an approx. 0.77m radius for the side wall projectors. For the floor, this was worse with a 0.7m radius estimate. We also found that at the border edges and corners, the deviations were not uniform resulting at most 0.10m offsets from the known dimensions. In particular, this was evident for edges that met the floor screen and corners towards the back end of the ReaCToR. By comparing the two maps of the known and estimated position values, we calculated



(a) 3D representation of the ReaCToR based on known dimensions



(b) 3D representation of projection accuracy

Figure 3.8: 3D representation of visual distortion error map

an error map for each projector. We then used this to update the projection model within the XVR platform by defining a set of configuration files and look up tables. This estimate also informed us the best position to place the GRAB arms within the ReaCToR, which was at its centre.

For head tracking, we used pilot studies to measure the consistency of the projection model at different positions within the working volume of the ReaCToR. Shown in Figure 3.7(b), we used a tripod with a reflective top, placed at known positions within the ReaCToR space. By projecting a 3D box on top of the tripod, we visually assessed variations in the perceived position at these locations. As these were subjective measures based upon observational differences, we took the average readings from each pilot test to produce a final output that was acceptable to then adjust the IS-900 calibration file. In general, we found that changes in viewing position was stable to 2-8mm, whilst rotations around the z and y axis produced drifting effects. These distortions only became obvious when matching physical points to virtual objects towards the edges of the ReaCToR workspace. Therefore, to encompass these errors, we defined a set shape and size of the 3D haptic contact point to a small grey sphere of 5cm in diameter for each arm.

For completeness, we also used this method to assess the accuracy of the VICON system for head tracking. This produced very stable results especially for head rotations. Nevertheless, due to the limited number of cameras, the working volume in the y axis was small and therefore unsuitable for head tracking with large user studies where participants could vary in height. As a result, we used this system to find the physical location of the GRAB haptic arms. With this information, we then aligned and maintained the precision of the 3D haptic contact points with respect to the implemented interaction technique.

3.3.3.2 Haptic Calibration Procedure

To align the local coordinate frame of GRAB haptic arms to the global reference domain, we implemented two calibration procedures: 1) to establish the local coordinate frame of the internal trackers of both GRAB arms 2) identify the correct mapping function needed to align the local coordinate frame of the haptic devices for a 1-to-1 correspondence with the visual projection system. As previously identified, the centre of the ReaCToR provided the best performance in terms of visual and 3D tracking alignment. Therefore, we positioned the GRAB arms to operate within this workspace.

In Figure 3.9(a), we projected a set of yellow crosshair markers on the floor of the ReaCToR to place each GRAB arm at a specific position. By using a set of white markers painted onto the base plates of each arm, we moved both GRAB arms to align with the yellow cross hair points projected on the ReaCToR floor. Once in this position, we then ran our first calibration procedure to establish the local coordinate frame of the internal trackers for each device.

For alignment between the two haptic devices, we positioned the mechanical arms parallel to the floor of the ReaCToR. By using a mechanical device supplied by PERCRO to link the arms together, we outputted the positional readings of the two coupled haptic devices whilst performing a set circular movement pattern. In this position, this left 3 translation DOFs free whilst keeping certain known elements fixed. When set, the right haptic arm was programmed to move through a set circular pattern as defined by the control box. This meant the left arm remained passive and was driven by the right. Based upon the outputs from both devices, we used the control software provided by PERCRO to compute coordinates of a pre-defined circular movement expressed in the local reference system of two arms. We then associated the two local frames of the right and left arms to an independent frame set.

This procedure was based upon the right arm being programmed with a pre-defined motion. It calculated the relative position vectors for each arm by applying a direct kinematic equation specific to the GRAB device. A set of regressive and statistical algorithms described in Dettori et al. were used to compute the relative position and local coordinate frames for each haptic device in metric units [DAM+03]. For consistency, we performed this procedure before every experiment.

Once establish, we identified the mapping function needed to align the local coordinate frame to the global frame defined by the XVR platform. By placing VICON markers around the base of both GRAB haptic arms, we found the physical position of the haptic device in reference to the dimensions of the ReaCToR. From this 3D position, we repositioned the 3D haptic contact points precisely 1cm in front of

(a) Positioning GRAB arms into the ReaCToR matching crosshair markers

(b) Map scaling function to global reference domain

Figure 3.9: Haptic calibration procedure

the thimble joints for each hand. As shown in Figure 3.9(b), these values were then used to reposition and orientate the local coordinate frame so that up/down, left/right and forward/back movements on the device would result in transformations in the x, y, z axes of the ReaCToR respectively.

By using the internal tracking information from the haptic device to control the position of the 3D haptic contact points, we wanted a 1-to-1 correspondence between their visual projection and physical movements made by the user. To assess this, we projected a series of targets to select in front of the device at known positions. By running a set of pilot studies, we evaluated the position values from the internal trackers of both GRAB arms to the known values of the projected 3D targets to assess their relationship. From these results, we found a mapping of 1.02, 0.88 and 1.0 for each of the x, y and z axes provided the best 1-to-1 alignment between the virtual movements made by the haptic contact points and the physical movements of the GRAB arms.

To summarise, we used the below calibration procedure to align the haptic devices before running each experiment:

1. Move the haptic arms to cross hair locations.
2. Position mechanical arms parallel to the floor.
3. Run initial haptic calibration procedure to establish the local coordinate frame of the internal trackers.
4. Initiate VICON tracking and alignment functions.
5. Assess and correct 1-to-1 mapping functions by selecting a series of virtual targets.
6. Start IVE experiment.

3.3.3.3 Haptic Control Features

To maintain consistent performance of the GRAB arms, we assessed the control features of the haptic arms. From this, we identified certain safety tolerances, in addition to operating requirements to maintain consistent force feedback cues for each user. Coordinating this, the control box managing the signals between the haptic device and the XVR platform played a significant role in ensuring the stability of the haptic simulation during its use. In particular, with help from PERCRO we implemented a set of functions for the safe usage of the device:

1. Manage the communication with the XVR platform.
2. Verify, change and store tunable mechanical values.
3. Provide an elementary safety sound feedback.
4. Model dynamic and kinematic movements of both haptic arms.
5. Compensate for non linear effects such as the gravity acceleration and friction.
6. Allow the XVR platform to act as a position controller and force display.

7. Monitor simulation parameters in order to prevent the haptic device hurting the user.
8. Generate the correct control motors signals for moving two arms and for activating the force feedback safely and without noise.

With these control features, we were able to define force vectors compatible with the GRAB arms from the XVR platform and its physic engine. To enabled the GRAB arms to behave in a consistent manner for each user and IVE experiment. In addition to the features described, this informed general design guidelines when sending force commands to the haptic devices:

1. Force feedback should be realistic allowing easy shape recognition.
2. Ensure high safety level in all control phases when activating force feedback vectors.
3. Incorporate software interface procedures for easy communication protocols with host IVE.
4. Introduce calibration features with the arms relative position and the IVE objects to maintain visual-haptic consistency throughout the simulation.

3.3.4 Hardware Performance Evaluation

To inform the design of suitable IVE experiments, we first assessed the performance of the developed hardware setup. Through this process, we established a set of operating constraints which were used to reduce the design space and conditions to evaluate. Furthermore, these parameters helped to identify unwanted factors, improving the reliability of the captured data sets characterising selection performance.

By analysing the specifications of the available hardware we identified: the usable movement space, viewpoint position, force feedback response, haptic point characteristics and experiment duration. Shown in Figure 3.10, we found the usable virtual workspace of the 3D haptic contact points with a fixed viewing perspective was of cubic size 3m, 0.6m and 15m for the x, y and z axes respectively. These boundaries represented the maximum positions whereby 3D objects could be easily seen without being affected by the resolution quality of the projection units. The minimum boundaries were discovered by evaluating positions where the physical architecture of the GRAB arms did not interfere with the projection of virtual objects. From this, we defined a working volume in front of the user where the 3D haptic points and targets were visually consistent. By establishing these parameters, this also informed the design characteristics of developed selection techniques.

From the computed projection error maps, we found that the centre of each of the ReaCToR produced the best visual-haptic correspondence. Characterised as a spherical volume, this overlapped the mechanical working space of the GRAB arms. Shown in Figure 3.9, we placed the arms 0.5m away from the front wall and 0.3m from the left and right walls, whereby all physical movements with the arms were performed within a 0.7m x 1m x 1m cubic area. Furthermore, to reduce the effect of visual distortions whilst users moved and rotated their heads, users had to stand at a specific position in the centre of the ReaCToR between the two haptic devices. In this position, the design of the setup was such that we could only evaluate forward facing interaction tasks.

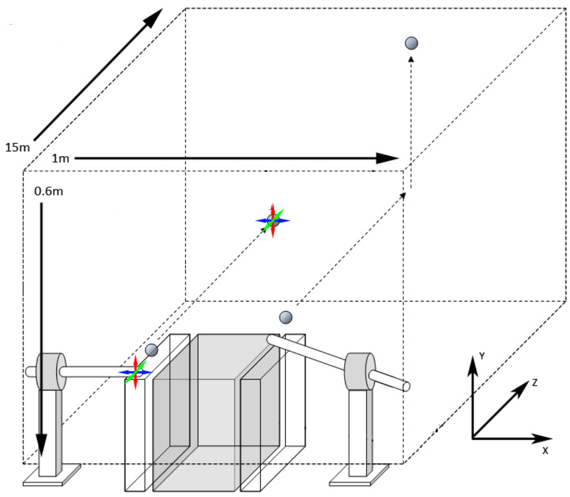


Figure 3.10: Maximum virtual operating workspace from a fixed viewing perspective

With respect to the size and shape of the 3D haptic contact point, this was based upon distortion errors from the head tracking and projection units. We found that a spherical shape of 5cm diameter was best, encapsulating the head tracking distortion with the IS-900. We placed the visual rendering of these points 1cm in front of the thimble joint for each GRAB arm as we found this was acceptable for co-located alignment and movement without resulting in visual interference with the mechanical architecture of the haptic device and 3D objects. Introducing this offset also meant we did not need to evaluate the shape and position of the thimble joint which was beyond the requirements of the system.

For reliable haptic force feedback cues, we decided a maximum force value of 4N was acceptable. As we only evaluated force feedback response upon contact, the implemented force commands would only push against the user's hands. To achieve a consistent experience of this maximum force value, we experimented with different ramping functions compatible with the control features of the haptic device. Whilst this resulted in a reduction of perceived stiffness performance, we were able to maintain a consistent reflection of force feedback from the devices through the simulation safely. We defined this ramping function based upon pilot studies outlining thresholds for responsiveness versus safety before each experiment. Furthermore, this evaluation helped identify force values that would not result in detrimental effects such as the user losing grip during movement when the device applied force.

To reduce the effects of simulation sickness and stereo discomfort, we limited the IVE experiments to 1 hour or less. Where possible, we incorporated rest times to reduce the affect of fatigue on the selection tasks and the performance measures collected. With regards to the colouring and shape of virtual objects used, we chose colours based upon brightness and how appropriate it was for the experiment. As discussed in chapter 5 onwards, we placed target objects within a natural scene to infer real world responses. We learnt these requirements by using an iterative process, collecting feedback from conducted experiments. For further details of these designs see chapters 4 and 5.

3.4 Experiment Methodologies

Evaluation frameworks used to assess 3D interaction can take many forms. Outlined by Bowman et al. this can include simple observational user studies, usability evaluations, and formal experiments [BH97] [DWS+99] [BKH97]. Further described by Gabbard and Hix, the design trends of these existing evaluation strategies flip between developing frameworks for specific application interactions, or generalising for a large range of tasks [HG97], [CB09], [BGH02]. Of those most suitable to this thesis, Lampton et al. and Bowman et al. proposed the use of a testbed approach for the assessment of 3D interaction techniques that contains a battery of standard interaction tasks [SP05].

By following a testbed approach, we narrowed the scope our IVE experiments to a small subset of well defined selection tasks which were also usable for a relatively large number of repeated trials. With this framework, we could run a variety of 3D selection technique using the same hardware configuration. This also helped in collecting a set of comparable user performance measures.

3.4.1 Testbed Experiment Design Guidelines

Described by Steed et al. the method of interaction is not the sole determinant of performance in an IVE application, rather there are multiple interacting factors [SP05]. Therefore, before designing our IVE experiments we identified four categories of factors that may influence user selection performance:

- *Characteristics of the task*- the required accuracy to complete the task.
- *The environment*- the number of objects, colours and shapes.
- *The user*- their spatial ability.
- *The system*- potential limitations of the hardware used.

Before finalising the design of any 3D selection technique and IVE experiment, we used pilot studies with expert users to evaluate the above factors. Explicitly addressed in chapters 4, 5 and 6, this helped to identifying certain threshold and operating constraints. To further reduce potential errors regarding participant variations and physical attributes, we also recruited people from similar age groups and background.

3.4.2 3D Selection Technique Design Guidelines

As the use of haptic force feedback within 3D selection techniques is relatively new, we carefully considered the suitability of each proposed design before implementing. Building upon work by Dam et al. and Bowman et al. we used the guidelines below when creating 3D selection techniques used in this thesis [Bow02] [vDHKG94]:

- Ensure that the 3D selection technique integrates user movement.
- Avoid repeated, frequent scaling of the user or environment.
- If possible, design the environment to maximise the perceived size of objects.
- If the application allows, use techniques requiring the user to control fewer degrees of freedom.

- When providing general aids make them generic and consistent.
- Avoid large haptic responses for user safety.

For specific implementation details of the distal and natural selections techniques created see chapters 4 and 5 respectively.

3.4.3 Performance Measures

For each IVE experiment, we captured a set of measures characterising the user performance of the presented 3D selection technique. Predominately, studies that evaluate 3D selection performance only consider movement time and accuracy (see section 2.5). For IVE platforms, we believe other measures such as the distance taken, velocity and trajectory of movement are equally important to understanding user performance. Therefore, by taking this broader view, we compiled a profile describing the selection behaviour of each participant using the below measures:

- Movement Time (MT). This was defined as the first moment at which movement was made from the set starting position to selecting the target.
- Distance Travelled (DT). This was the total size of the trajectory taken to select an object from the point at which movement is made from the starting position to selection.
- Velocity Taken (VT). Movement Time divided by Distance Travelled.
- Real-time 3D position- 3D position vector referencing the global coordinate frame. This was used to analyse the trajectory taken to task completion.
- Impact points and their specifications (IPDT). These are the points made on the target surface used to select the object.

Since the above measures are correlated by VT = DT / MT, movement time must have a strong relationship to the distance travelled and the speed of movement to task completion.

We were also concerned with qualitative factors such as how natural the interaction was to use. Therefore, by using a set of usability questionnaires, we recorded ratings describing the ease of use, the ease of learning, and user comfort for each selection technique assessed. By analysing both quantitative and qualitative data, we wanted to extend the research beyond speed and accuracy observations. For factors that were not objectively measurable, we used standard questionnaires for simulator sickness and subject/experimenter reports [CCW+12] [KLBL93] (see Appendix A).

To log the quantitative information in real-time, we created a discrete logging system. Depicted in Figure 3.6, the position and rotation information was sent via a UDP connection to a remote PC. With this setup, we removed the write function from the main simulation loop as not to interfere with the synchronisation of the visual and haptic cues. These log files were then filtered using Matlab for further offline data analyse (see Appendix A, B and C).

We used a broad range of statistical methods to analyse the recorded data. Building upon initial experiments from chapter 4, by chapters 5 and 6 we examined user performance using the following graphs and tables describing:

1. Average, standard deviation and ANOVA analyse for MT, DT and VT to task completion separated by selection task type and feedback condition.

2. Average difference, standard deviation and ANOVA analysis for MT, DT and VT to task completion between haptic conditions separated by selection task type.

3. Average difference, standard deviation and ANOVA analysis for MT, DT and VT to task completion between selection task type separated by haptic condition.

4. Velocity profiles for each task and haptic condition. Introduced in chapter 5, we plotted the change in distance with respect to the change in time when moving between targets to task completion. By doing so, we evaluated the acceleration and deceleration behaviours between targets when using different haptic conditions.

5. Trajectory maps defining movement from start position to selection. Introduced in chapter 5 and based upon results from chapter 4, we modified the logging system to record the 3D position vector in real-time. With this data, we plotted the trajectory for each axis plane representing the ballistic movements taken by participants when selecting targets. In addition, we were able to examine the behaviour used upon contact with virtual objects for each haptic condition assessed.

6. Movement time (MT) versus index of difficult (ID). In chapter 6, we examined the recorded movement time results with respect to Fitts' law. By plotting MT against the tasks ID as defined by equation 2.1, we computed a set of correlation coefficients in reference to studies by Mcguffin and Balakrishnan [MB05].

3.5 Summary

In this chapter we outlined the implementation of the hardware setup used to display the evaluated selection techniques and haptic force feedback conditions. We also discussed the design guidelines used to build a suitable evaluation framework for this thesis. In particular, we explicitly discuss the validity of the created IVE experiments by describing how we reduced the effects of any distracting factors caused by the available hardware. With these methods defined, in chapter 4 we begin our assessment of haptic force feedback when using distal selection techniques within an IVE.

Chapter 4

Haptic Force Feedback Effects on Distal 3D Selection

4.1 Overview

In this chapter we evaluated the effects of haptic force feedback on two established distal 3D selection techniques: Arm Extension (AE) (section 4.6) and Velocity Based Travel (VBT) (section 4.7). For both, we assessed their performance by creating an IVE experiment that displayed a common set of 3D selection tasks. Described in section 4.5.1, we used this framework to render two experiment conditions: with and without haptic force feedback. We also implemented two transfer functions for each selection technique, to then discuss their performance differences with respect to haptic force feedback.

For each experiment condition, we collected qualitative and quantitative data sets. Separated by selection technique, we analysed these measures by profiling the movement strategies used for each transfer function and haptic condition. To describe this work, we used the sections below:

- *Distal 3D Selection Techniques (section 4.2)*- Characteristics of distal 3D selection techniques.

- *Examples of Common 3D Interaction Techniques for IVEs (section 4.3)*- Taxonomy of common 3D interaction techniques. We used these examples as a basis for designing the selection techniques implemented in the user studies.

- *Experimental Aims and Expectations (section 4.4)*

- *Design of Experimental Framework (section 4.5)*- Description of the evaluation framework, haptic feedback conditions and IVE experiment used to assess the implemented 3D selection techniques.

- *Experiment I- Arm Extension Selection Techniques (section 4.6)*- User study outlining the effects of haptic force feedback on the implemented arm extension selection techniques.

- *Experiment II- Velocity Based Travel Selection Techniques (section 4.7)*- User study outlining the effects of haptic force feedback on the implemented velocity based travel selection techniques.

4.2 Distal 3D Selection Techniques

When designing a selection technique, we can either define methods that attempt to mimic real world responses or conversely use more 'distal' metaphors. Within IVE platforms, we map the user's own body to perform actions within the 3D space. One form of this is a direct manipulation model that relies on replicating real world interactions [Sch83]. For example, if a user wants to pick up an object they must perform the real world gesture of reaching out to grab the target with both hands. When designers integrate this type of interaction model, they can quickly create an environment where the programmed actions are intuitive to perform and representative to real world tasks. However, achieving this level of precision between the connected multimodal display devices is hard [ISLM01]. Due to the difficulty of tracking the user's body and the lack of good physical models for the end efforts, designers often avoid implementing a real world interaction metaphor.

The design of 3D selection techniques fall into two opposing directions: isomorphic and distal interaction models. The isomorphic view suggests that a strict geometrical and temporal 1-to-1 correspondence between motions in the physical and virtual worlds provides the most natural form of interaction [BH97]. Results of early human factor studies by Knight et al. support this view, demonstrating that the overall experience of the simulation with isomorphic interaction was easier and more intuitive to use [KL87]. Nevertheless, as discussed by Bowman et al., when developing natural or isomorphic selection techniques, there are two important shortcomings to consider: 1) these mappings are often impractical because of constraints with respect to the input devices, such as a small working volume or a restricted tracking range, 2) isomorphism is often ineffective because of the limitations of humans. For example, our arms can only cover a small distance defined by the size of our body, acting as a barrier when interacting with targets beyond this workspace [BKLP05]. As a result, researchers argue the advantages of using distal interaction techniques, highlighting their effectiveness in specific tasks more appropriate to the application objectives.

Distal interaction techniques provide 'magical' ways of interacting within the virtual environment by translating the user's body movements using unconventional mappings. For example, virtual tools such as voodoo dolls and others discussed in section 4.3, use a non-physical representation that the user can control through their body movements which are then transformed in some way to aid the presented task [PWF00] [PWBI97a]. From a design perspective, the scope is large, as we can define distal selection techniques using many types of mappings, functions and transformations suitable for the application. As long as the intended design is beneficial to the user, these techniques can manipulate 3D objects in quite different ways to natural forms of interaction and overcome certain human limitations.

When comparing the advantages of using a distal interaction technique over more natural or isomorphic methods, this is dependent on the application and the goals of the simulation. Researchers commonly believe that an isomorphic interaction technique is better for most cases, as users can perform complicated interactions by intuitively building upon previous knowledge from the real world [JR90]. In particular, this can lead to more generalised forms of interaction which the user can combine to perform complex tasks. However, for applications constrained by human and hardware limitations, such as selecting objects placed beyond arms reach, we need to implement a distal method of interaction that decouples the users real world reference points. Whilst this can lead to further problems, it is commonly thought that users have the capacity to learn these new methods of interaction and become proficient [SSC02]. However, we always need to consider the cost of these design decisions with respect to interaction performance and other factors. As isomorphic techniques that impose strict realism are technically hard to achieve, at present the more established methods of 3D interaction use distal implementations.

4.3 Examples of Common 3D Interaction Techniques

To give an overview of different types of 3D interaction techniques, in this section we discuss methods currently established in the literature. For our experiments, we used these examples as a starting point to define suitable case studies for evaluating the effect of different types of haptic force feedback conditions on 3D selection. A full review of all 3D interaction techniques is beyond the scope of this thesis. For further information see [Han97] [RB07] [BKLP05] [vDHKG94] [OS03].

4.3.1 Interacting by Pointing

Pointing is a powerful selection technique. It provides users the ability to easily select and then manipulate virtual objects located anywhere in the 3D space. A vector is used to intersect the surface of a virtual object so that users can then select it by triggering a collision event confirming selection [KBSM10]. Upon selection, additional functions are often used such as attaching the target object to the end of the pointing vector for further manipulation tasks.

A number of evaluations demonstrate that pointing interactions result in better selection performance than virtual hand techniques. Pourpyrev, Weghorst and Bowman showed that pointing requires significantly less physical hand movements from the user resulting in better user performance compared to a 'classical' virtual hand technique [PWBI97b]. However, pointing can only accomplish object manipulation efficiently in radial movements and when the task does not require changing the distance between the users and objects [MSB91] [Han97] [GB04].

Common examples of pointing selection techniques are: simple ray-casting technique, two handed pointing, flashlight technique, aperture technique, image-place techniques and fishing-reel technique [Han97] [BKLP05].

4.3.2 Simple / 'Classical' Virtual Hand

The simple virtual hand technique is a direct mapping of the user's hand motion to a virtual hand representation within the IVE. By using this approach, designers can map the interaction points in the IVE directly to the hand movements of the user, creating an intuitive link between physical and virtual objects [BKLP05]. This makes virtual hand techniques easy to learn as they can simulate how we grasp objects in the real world. However, a fundamental problem with these techniques is that users can only select and manipulate objects within their arms reach. Therefore, to select objects located further away, the user must employ an additional locomotion technique to move towards the target object.

4.3.3 Two Handed Grab / Grasp Metaphor

This technique is similar to virtual hand but requires cooperative movement from the user's hands. Described as a grab metaphor, users can only manipulate a 3D object when both hands are in contact to its surfaces, similar to how we pick up a large, heavy box in the real world [BH97]. Consequently, only pushing and stacking style interactions are possible. Again, whilst this metaphor is very intuitive, the lack of good end effector models limit the possibility for more intricate types of interactions.

4.3.4 Go-Go Hand

Go-Go hand techniques attempts to improve on virtual hand by providing a simple and unobtrusive technique that allows the user to interactively change the length of the virtual arm [PBWI96]. It can provide a simple way to interactively control the length of the virtual arm by stretching the interaction point out or bringing it closer. The main difference between Go-go hand and virtual hand techniques is that users can use different mapping functions to achieve varying control-display gains between the real and virtual interaction points.

In comparison to other interaction techniques, this methodology provides direct, seamless, 6 DOF object manipulation both close to the user and at a distance. It allows the user to both bring far away objects near, or move near objects further away. However, the maximum afforded reaching distance is still finite. Furthermore, as distance increases Go-go hand also maps small movements of the user's hand into large movements at the virtual interaction point, which has a detrimental effect to precision when selecting at distance. A number of studies have evaluated Go-Go hand in a subset of manipulation tasks, and all found that users did not have any difficulties understanding it [BH97]. However, as a selection technique, Go-Go hand was less effective than ray casting [PWBI97b].

4.3.5 World in Miniature

An alternative to extending the length of the user's arm is to scale the entire world and bring it within reach. The World in Miniature (WIM) technique provides the user with a miniature handheld model of the virtual environment which is an exact copy but at a smaller scale. The user can indirectly manipulate virtual objects by interacting with their representations in the WIM [SCP95].

WIM allows easy object manipulation both within and outside of the area of user reach. It can also combine navigation with manipulation, because the user can also move his or her virtual representation in the WIM. However, this technique does not scale well [BKLP05]. Although WIM works relatively well for small and medium-sized environments, such as the interior of a virtual building or rooms, when using WIM in a very large environment this would result in a scale factor that would make surroundings objects very small - making accurate selection and manipulation tasks difficult.

4.3.6 Velocity Based Travel Techniques

In contrast to pointing, travel techniques attempt to move the user's perspective towards the intended target. Within large IVEs, this is a useful method of interaction as we are able to maintain the initial relationships between the user and interaction points whilst traversing all positions within the virtual environment. For example, as shown in Figure 4.1, when triggered (often a button event or boundary

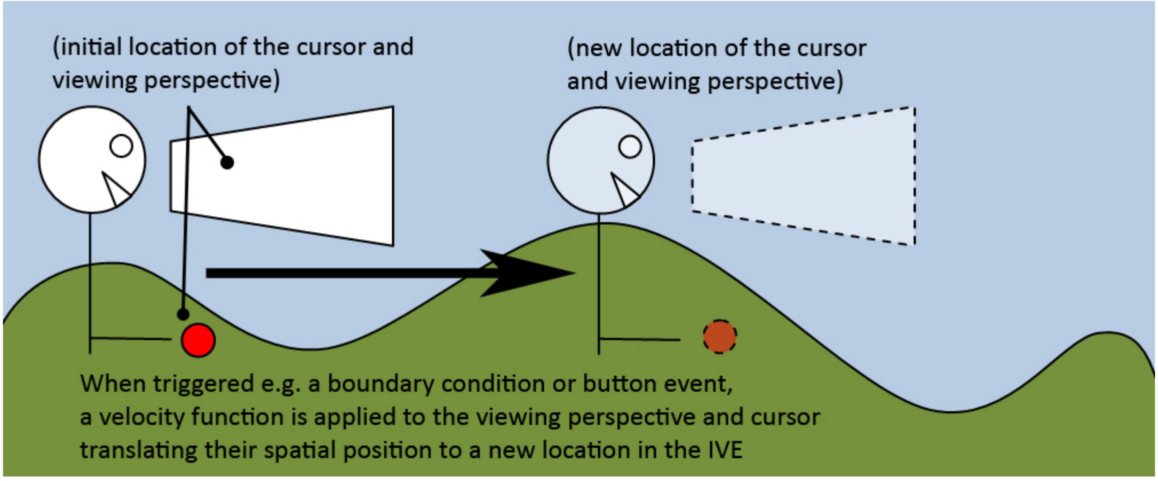


Figure 4.1: Example of a velocity based travel technique

condition), the user applies a velocity function to the spatial position of both their cursor and viewing perspective. Sometimes described as 'flying', this action moves the user through the IVE. Outlined by Bowman, travel techniques are an important and universal user interface which needs to be better understood and implemented in order to maximize user comfort and productivity in IVEs [BKH97].

From previous work defining the taxonomy of different virtual travel techniques [BDHB99] [BKH97], these studies clearly identify velocity control as a key component. Mine et al. classifies five different methods to specify the speed of motion (constant speed, constant acceleration, hand (gesture) controlled, physical controls, and virtual controls) in order to understand the principles of velocity control techniques [SP05] [Min95b]. Furthermore, Bowman et al. list several velocity control metaphors in the taxonomy of virtual travel techniques [BKH97]. Brogan et al. used stationary bicycles to control the user's velocity, whilst Couvillion et al. created a pressure-sensitive mat and tracked footsteps made on the device[BMH98] [CLL01]. Other studies that include force feedback within their interaction techniques such as FORVE demonstrate efficiency gains when specifying velocity and acceleration in IVEs [JJK+04]. Another device used to control the speed of travel is the Bungee Bat, which is a 3D passive force feedback device [PW94]. As these methods have been developed for specific input devices, care must be taken to balance the design of any velocity based travel technique to the constraints of the hardware available.

4.4 Experimental Aims and Expectations

The aim of the two experiments presented in this chapter was to investigate the effects of haptic force feedback on different types of arm extension (section 4.6) and velocity based travel selection techniques (section 4.7). Of particular interest was to identify how different combinations of visual and haptic conditions changed the strategies used to perform a 3D selection task.

To evaluate a wide distribution of 3D selection tasks with different types of difficulty, we decided to change the number of targets to select and their displacement. For both selection techniques, the basic hypothesis was that the addition of haptic force feedback will help, but also have a hindrance to task completion. Depending on the difficulty of the task, ranging from selecting multiple targets placed far away, to a single target within arms reach, we expected to find differences in the way in which haptic feedback was used to complete these types of selection tasks. In particular, we believed to find instances whereby haptic feedback improved, but also had a negative effect on performance by making users take slower or longer paths to task completion.

When moving to select a single target, we expected that the combination of visual and haptic feedback to improve selection performance. Following an information theory perspective, due to the extra bandwidth provided by displaying haptic feedback this will help the time taken to touch a single target. Conversely, when performing more complex selection tasks involving more than one target, we believed haptic feedback will hinder performance. In this scenario, users would need to put in more work by having to move around targets that provide physical resistance to achieve task completion.

For both conditions, with and without haptic force feedback, these performance characteristics will be define by different profiles in MT, DT and VT (section 3.4.3). At this stage, we had no prior expectations to the movement behaviour observed for each selection technique.

4.5 Design of Experimental Framework

We conducted two experiments to evaluate the performance of different types 3D selection techniques: Arm Extension (section 4.6) and Velocity Based Travel (section 4.7). To provide relevance, we chose these designs as they built upon previous work on Go-Go hand and velocity based travel techniques commonly used within IVEs. For both selection techniques we used the same apparatus setup. Discussed in section 3.3.4 , we tailored the implemented selection techniques to the characteristics of the ReaCToR and GRAB haptic devices. This also helped to identify and limit the effects of any distracting factors to selection performance unique to this setup.

We ran all of the implemented selection techniques through the same IVE experiment. By following a testbed design approach, we compared the user performance of these selection techniques within a common hardware and experimental domain. This also enabled the evaluation of user performance based upon completing a set of generic and highly repeatable 3D selection tasks.

We developed two types of haptic force feedback configurations: selection with and without haptic force feedback. Both haptic conditions were implemented for the IVE experiment and acted as independent variables. By running each selection technique through the same IVE experiment, we collected a set of qualitative and quantitative performance measures comparable between haptic force feedback conditions. Unlike other studies that evaluate MT to task completion only, we also recorded DT and VT (section 3.4.3). As a result, we designed a within subjects experiment separated by haptic feedback condition. Code developed for this study is presented in Appendix A.

4.5.1 Implementation of IVE Experiment

The IVE experiment consisted of 9 sphere targets placed in random positions within a defined volume space. By placing these targets at different distances away from the participant, we created an evaluation framework whereby the performance of the presented selection technique could be recorded under different haptic feedback conditions. Both haptic devices were used to manipulate in real-time two 3D haptic contact points presented initially in front of the thimble joints. With this setup, we instructed participants to manoeuvre these interaction points and select different spatial arrangements of yellow and red sphere targets.

To describe the virtual objects we used three bold colours representing the targets to select first and those to avoid. Shown in Figure 4.2, participants were instructed to select yellow then red sphere targets placed in a pre-defined order:

1. *One yellow sphere*- representing the first target to select.

2. *One red sphere*- last target to select after selection of a yellow sphere.

3. *Seven blue spheres*- obstacles in the scene to avoid.

The colour and size of the virtual objects were chosen by running a set of pilot studies with expert users. From these trials, we chose targets with fixed dimensions of 10cm radius and spatial arrangements suitable for the experiment. To limit the effect of any distracting factors, we also used a white back drop to the virtual environment and rendered a thinly lined reference grid in the XZ plane to give a horizon level. Within this environment, participants could move the two haptic contact points freely as defined by the presented selection technique. Only upon collision with other virtual sphere targets and obstacles did we activate haptic force feedback. The implementation of the assessed haptic feedback conditions is discussed in section 4.5.2.

Upon completing a selection task, we programmed the simulation to stop and reset the view point and 3D haptic contact points to their initial position taken before the start of the experiment. At this point, we displayed a new spatial arrangement of targets and obstacles, placing all 9 spheres in new positions to then start a new selection task. By using this procedure, we ensured that each task started from the same position. We repeated this process until covering a large variety of pre-defined distance combinations between yellow and red sphere targets.

To help classify the different distance combinations, we established three difficulty settings based upon how far away the target objects were from the initial starting position of the participant:

1. *Small range*- 0.0m to 3.0m, targets placed in this band are easy to select.

2. *Middle range*- 3.0m to 8.0m, targets placed in this band are moderately difficult to select.

3. *Large range*- 8.0m to 15.0m, targets placed in this band are hard to select.

By using this segmentation, we defined 9 types of selection combinations to evaluate. Again, from the pilot studies, we reduced the type of distance combinations to evaluate forward ballistic movements only, limiting interactions that involved a backward trajectory found to be difficult to perform.

1. *Small (SelectS)*- selection of one yellow target placed in the small distance range.

2. *Medium (SelectM)*- selection of one yellow target placed in the medium distance range.

3. *Large (SelectL)*- selection of one yellow target placed in the large distance range.

4. *Small-to-Small (SelectSS)*- selecting first one yellow and then red sphere targets both placed within the small distance range.

5. *Small-to-Medium (SelectSM)*- selecting first one yellow sphere placed in the small distance range and then one red sphere placed in the medium distance range.

6. *Small-to-Large (SelectSL)*- selecting one yellow placed in the small distance range and then one range in large distance range.

7. *Medium-to-Medium (SelectMM)*- selecting first a yellow then red targets both placed in the medium distance range.

8. *Medium-to-Large (SelectML)*- selecting one yellow target placed in the middle distance range and then red target placed in the large distance range.

9. *Large-to-Large (SelectLL)*- selecting a yellow then red target placed in the large distance range.

Following the ergonomic studies of the connected devices in section 3.3.4, we placed all of the distance combinations within an identified volume range. Based upon known limitations from the ReaCToR, haptic devices and selection technique characteristics we defined the below volume size referenced to the centre of the ReaCToR:

1. *X-axis*- -0.5m to 0.5m.

2. *Y-axis*- -0.3m to 0.3m.

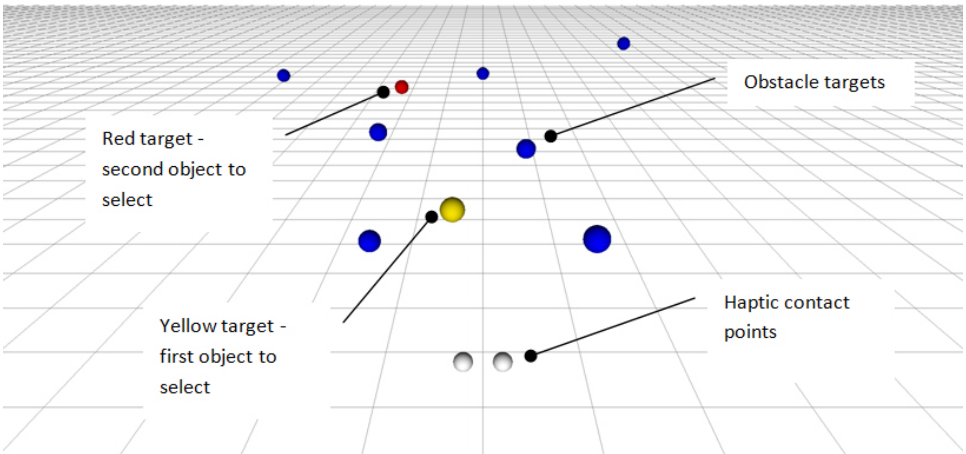
3. *Z-axis*- 0m to -15m.

Whilst including obstacles provided extra a degree of difficulty to the assessed selection tasks, we were careful to ensure the distribution of these objects did not unduly affect user performance. Again, by conducting pilot studies with expert users, we selected spatial arrangement of spheres that had an even distribution of obstacles which were at least 0.2m away from the target objects. We also used this pre-evaluation phase to generate a list of target spatial arrangements to ensure we assessed a good range of distance combinations between target objects.

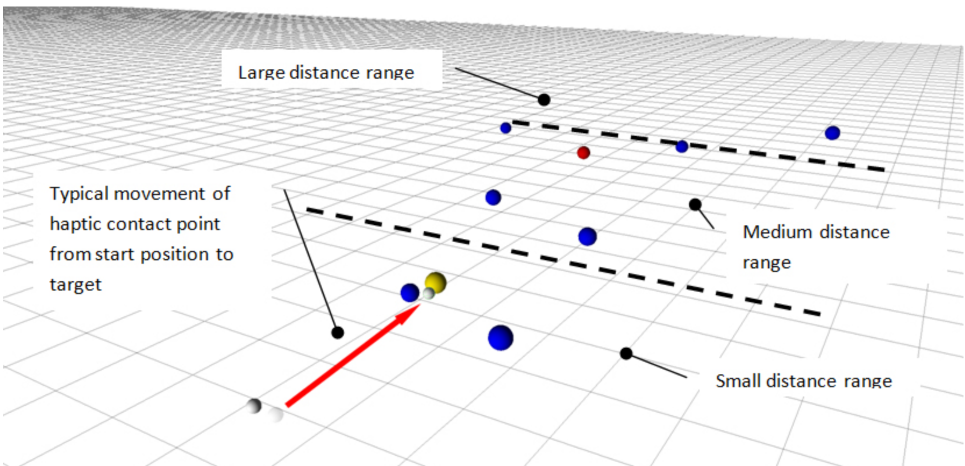
In total, we defined 5 selection tasks for each of the outlined distance combinations. Consequently, participants performed 45 individual selection tasks, for each haptic force feedback condition and selection technique. Discussed in sections 4.6 and 4.7, for both arm extension and velocity based travel techniques, we implemented a linear and non-linear transfer function. Therefore, participants selected targets using two a linear and non-linear selection technique but with only one haptic condition. Summarised in Table 4.1, this led to 90 individual selection tasks being displayed for each trial.

Table 4.1: Number of selection tasks for each interaction technique and haptic feedback condition

		Number of selection tasks within distance combination									
Haptic Condition:	Interaction Technique	SelectS	SelectM	SelectL	SelectSS	SelectSM	SelectSL	SelectMM	SelectML	SelectLL	Total
NoF condition											
	Arm Extension:										
	- linear	5	5	5	5	5	5	5	5	5	45
	- non-linear	5	5	5	5	5	5	5	5	5	45
	Velocity Based Travel:										
	- linear	5	5	5	5	5	5	5	5	5	45
	- non-linear	5	5	5	5	5	5	5	5	5	45
HtF condition											
	Arm Extension:										
	- linear	5	5	5	5	5	5	5	5	5	45
	- non-linear	5	5	5	5	5	5	5	5	5	45
	Velocity Based Travel										
	- linear	5	5	5	5	5	5	5	5	5	45
	- non-linear	5	5	5	5	5	5	5	5	5	45



(a) User view



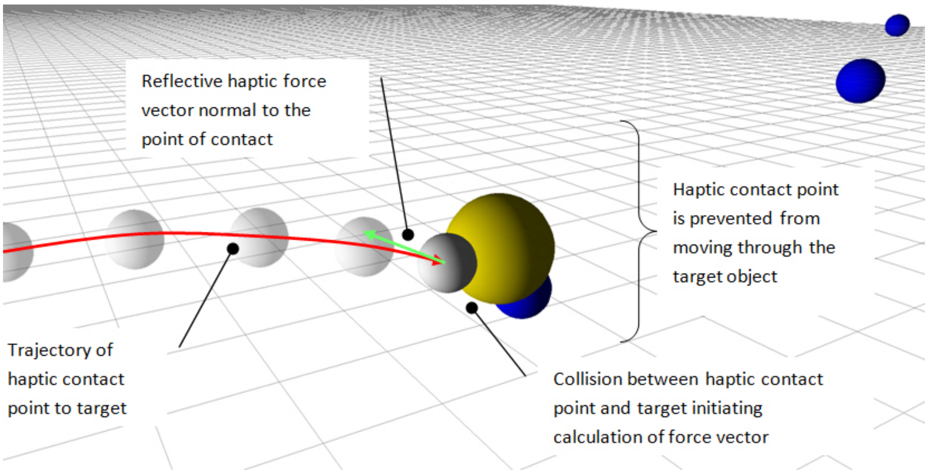
(b) Perspective view with distance markings

Figure 4.2: Example of IVE experiment and its design

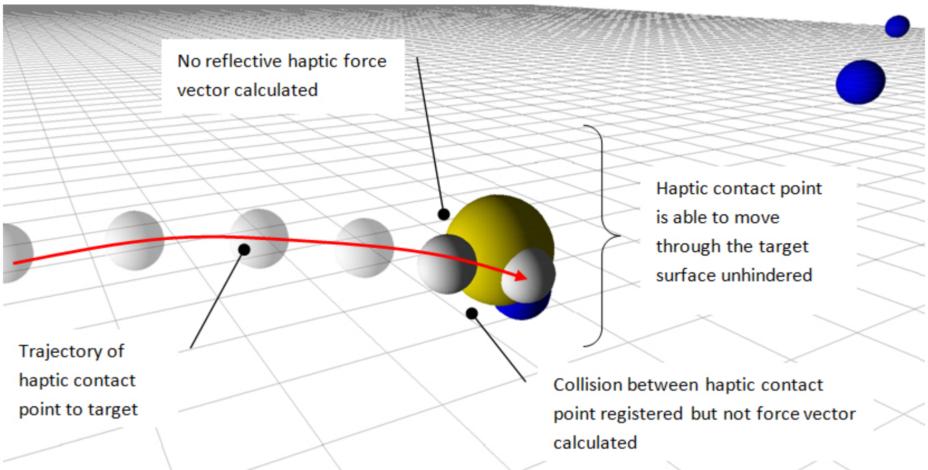
(a) Side view

(b) Behind view

Figure 4.3: Hardware setup for arm extension and velocity based travel selection techniques



(a) Selection with targets providing haptic force feedback



(b) Selection with targets without haptic force feedback

Figure 4.4: Examples of haptic implementations used within IVE experiment

4.5.2 Implementation of Haptic Force Feedback Conditions

For the designed IVE experiment, we created two haptic feedback conditions:

1. *Selection without haptic feedback (NoF condition)*- Participants given visual feedback of the IVE only. Upon selection between 3D haptic contact and surrounding objects, we did not provide a force feedback response. We also did not provide a visual collision detection response.

2. *Selection with haptic feedback (HtF condition)*- Visual + haptic feedback. Upon selection participants experienced haptic force feedback displayed through the GRAB devices. Similar to the NoF condition, we did not provide a visual collision detection response. Unlike the NoF condition, participants would feel a force feedback response upon selection between the haptic contact points and another 3D target.

For conditions when we provided haptic feedback, this was only activated upon selection between either haptic contact points and the surrounding 3D objects. Shown in Figure 4.4, when a haptic contact point selected or collided with another target, we calculated a force vector which was then displayed through the GRAB arms to impede movement. Discussed in section 3.3.1, this calculation was done by the XVR physics engine running in real-time with the simulation, outputting the reflective force vector normal to the collision between the haptic contact point and 3D objects. In addition, we implemented a maximum feedback response of 4N to represent a hard contact upon selection. This value was established through pilot studies, creating an interaction whereby users could successfully experience haptic force feedback without causing any distracting effects such as unexpected kicking of the device.

In contrast, when selecting targets that did not provide haptic feedback, participants were able to select a target without being impeded by force feedback being displayed on the GRAB haptic devices. Shown in Figure 4.4, when a haptic contact point selected another object, we registered this collision but did not display a force vector. The resultant interaction enabled the visual selection of objects without feeling a haptic response upon collision, thus being able to go through the surface of the target.

For further information on the implementation of the evaluated selection techniques see sections 4.6.1 and 4.7.1.

4.6 Experiment I: Arm Extension Selection Techniques (AE)

In this study, we evaluated the user performance of different arm extension selection techniques with respect to two haptic force feedback conditions. We implemented two types of arm extension techniques that used either a linear or non-linear transfer function (section 4.6.1). By running each of these techniques through the same IVE experiment, we collected performance data for selection under conditions with / without haptic force feedback.

4.6.1 Implementation of Arm Extension Selection Techniques

Following Poupyrev's design of a Go-Go hand interaction technique, we implemented two types of arm extension techniques that used different transfer functions [PBWI96]. Shown in Figure 4.5, participants manoeuvred both GRAB arms to control two 3D haptic contacts points for each hand and select a series of 3D targets. Initially positioned 1cm in front of the thimble joints, participants were able to move and extend the displacement of the 3D haptic contact points within the IVE in reference to the presented arm extension technique and transfer function.

To visually represent the haptic contact points, we defined these as two 3D spheres. Through piloting with expert users, we chose a grey colour to contrast with the other objects in the virtual environment. Outlined in section 4.5.1, we set the size of these points to 5cm in diameter to encompass any distortion effects caused by the tracking sub systems. Defining movement, physical displacements along the x, y and z axes of either haptic arm transformed the starting position of their corresponding 3D haptic contact point in real-time and mapped to the programmed transfer function. For example, if a participant moved their left hand 3cms, the left 3D haptic contact point would move in the same direction but with a displacement controlled by the implemented transfer function governing overall movement. As both haptic devices only offered 3 DOF, we did not map any rotational transformations made by the hands. Furthermore, we did not integrate any form of gaze control.

Shown in Figure 4.5, we defined the maximum movement space of the two 3D haptic contact points based upon the limitations of both the display and haptic devices. This was defined as the maximum displacement in each dimension whereby participants could easily view and access virtual objects. As the viewing perspective was fixed and did not travel with movements of the haptic contact points, the ability to identify far away targets was affected by the resolution quality of the display device. Through piloting, we found that the maximum displacement along the z axis to be 15m - the point at which the visual cues describing the haptic contact became too small to see with a fixed viewing position at the centre of the ReaCToR. From these results, we defined the workspace of the implemented arm extension techniques to be:

- +-0.5m along the x axis.
- 15.0m along the z axis in the forward direction.
- -0.3m and +0.3m along the y axis- we limited the height of the workspace as the ReaCToR did not have a screen on the ceiling.

To test different types of arm extension techniques, we designed a linear and non-linear transfer function. Based upon movements of either hand made through the GRAB arms, the transfer function would map 3D haptic contact points further into the virtual space. Following work by Bowman et al., we designed the transfer functions to first obtain the raw direction and magnitude components as measured by the hardware. This was then used to apply a transformation mapping and represent a new extended position of the 3D haptic contact points in the IVE. To define suitable linear and non-linear mappings, we used pilot studies to establish these values best fitting to the hardware setup [BKLP05]:

Linear mapping:
For each dimension, we used the following displacement mappings:

$$x_d = 1.66x_{hp} \tag{4.1}$$

$$y_d = 1.5y_{hp} \tag{4.2}$$

$$z_d = 37.5z_{hp} \tag{4.3}$$

- x_d, y_d, z_d- new displacement of haptic contact point in the 3D space.
- x_{hp}, y_{hp}, z_{hp}- displacement of thimble joint of the haptic arm.

Non-linear mapping:

An exponential transfer function was implemented to translate the haptic contact point to the limits of the extended workspace of the IVE. We used the below functions for each dimension:

$$x_d = 1.2^{x_{hp}} \tag{4.4}$$

$$y_d = 1.2^{y_{hp}} \tag{4.5}$$

$$z_d = 1.2^{z_{hp}} \tag{4.6}$$

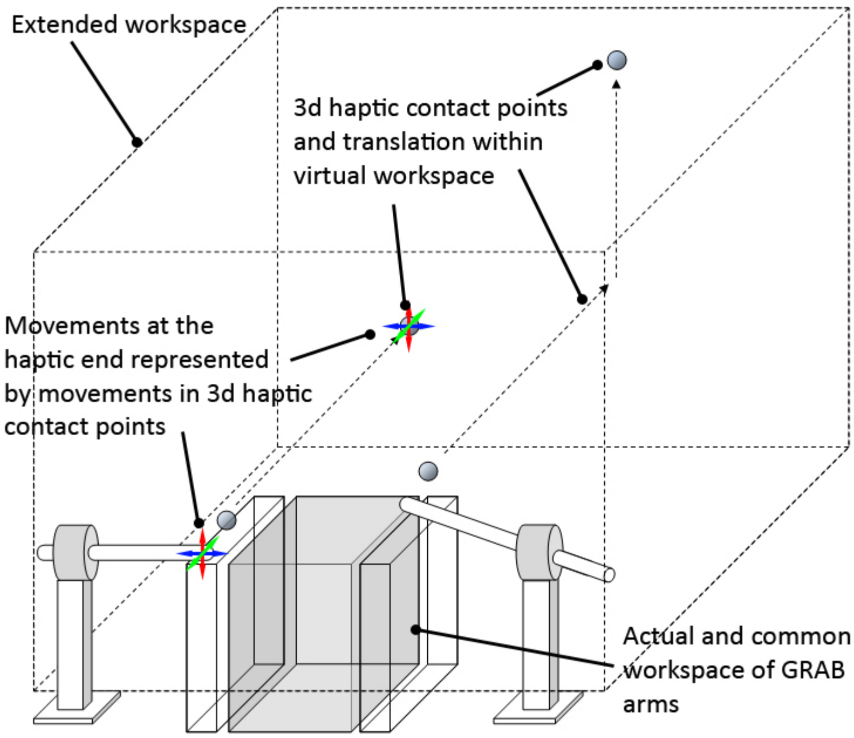
- x_d, y_d, z_d- new displacement of haptic contact point in the 3D space.
- x_{hp}, y_{hp}, z_{hp}- displacement of thimble joint of the haptic arm.

4.6.2 Experiment Procedure and Participants

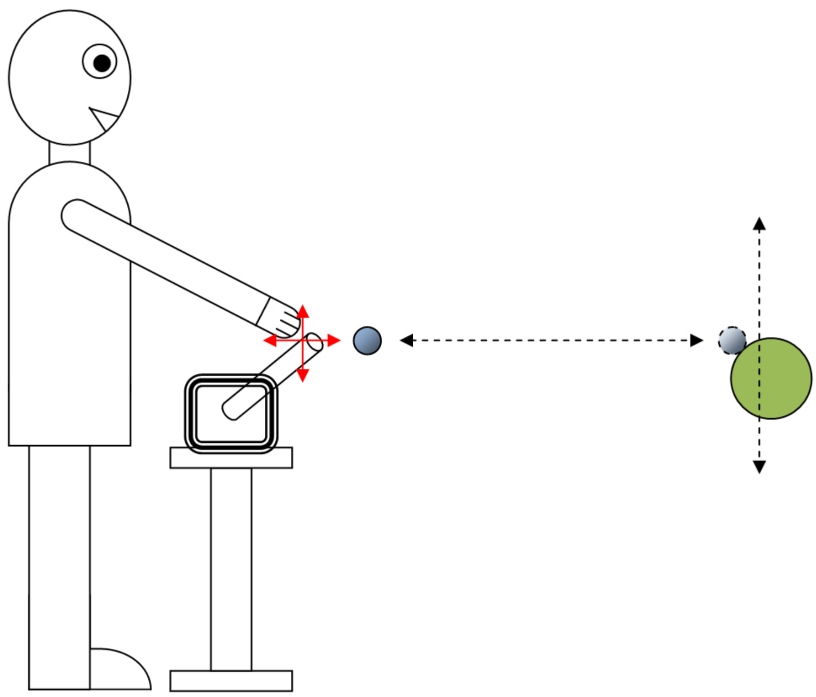
We evaluated 40 participants (37 male and 3 female), 20 for each haptic force feedback conditions. For each trial, each participant selected targets for both arm extension techniques but with only one haptic condition. A breakdown of the participants is given in Table 1 (see Appendix A).

To reduce any carry-over learning effects between the selection techniques presented, the order in which they were used was randomised. Before starting the experiment, each participant was given a pre-questionnaire outlining general guidelines, the departmental ethnics code covering these types of user experiments, and the context of the work (see Appendix A). Also, at this stage, we asked general background information indicating that all the participants were right handed and all rated their experience of 3D games as 'good' or above (defined as 10 hours or above playing video games per week). In terms of the demographic of the participants, they were taken from members of the Department of Computer Science at University College London and post-graduate students. 8 participants had previously used the ReaCToR but not the GRAB arms.

Before starting the experiment we gave each participant a demonstration of the equipment and a thorough induction. Each participant had 10-15 minutes to accustom themselves with the GRAB haptic



(a) Extended workspace



(b) Manipulation of haptic contact points

Figure 4.5: Design of arm extension selection technique and extend workspace volume

interface, ReaCToR, head tracking and the presented interaction technique under both haptic conditions to level out any learning effects. Once done, we repeated the instructions, answered any questions, and asked if the participant was ready to start the experiment.

Once started, we logged measurements during the experiment. The experimenter also maintained a discrete observation post and kept notes of the behaviour of each participant describing the strategies taken to complete the selection tasks. After completion, every participant was given a 15 minute break and then asked to fill a usability questionnaire for the arm extension technique (see Appendix A). We created the usability questionnaire based upon on work by Bowman, Gabbard and Hix [BGH02]. When finished, another 5 minute break was given before starting the remaining arm extension technique.

Again, we gave full instructions before starting the final experiment condition. Another set of the same usability questionnaires were also given at the end. In total, the experiment lasted 1 hour and each participant was compensated with a monetary reward at the end.

We used a between subjects design to evaluate the different haptic conditions. This was done so that we could evaluate multiple variables at once. Due to this design consideration it was important that we performed the experiments with a large number of participants. No explicit instructions were given to complete the tasks as quickly or accurately as possible. Though participants were asked to complete the tasks by selecting the targets in the correct order.

To clarify, as the experiment was designed to be a series of repetitive tasks thinking time was not independently evaluated. Also, at the start of each trial we included 15 selection tasks that we discounted in the results, as to eliminate the learning effects on the data of the participants at the start the experiment. When participants made false movements, defined as selecting targets in the wrong order, this was logged by the experimenter and excluded from the results. Nevertheless, all other movements were included.

4.6.3 Results- Linear Arm Extension (L-AE)

4.6.3.1 Movement Time (MT)

When moving to select a single target (Select1), MT was quickest under no force feedback conditions. From Table 4.2, the average difference in MT under NoF conditions compared to selection with haptic force feedback for SelectS and SelectL was less by 0.353 seconds and 1.219 seconds respectively. In contrast, for SelectM MT was quicker under HtF conditions by 0.431 seconds. Other observations between haptic conditions included larger standard deviation results for SelectM and SelectL when selecting targets without force feedback. These findings suggest an interesting trade-off in MT performance between haptic feedback condition and target distance. Whilst participants were able select targets with less MT under no force feedback conditions, the variability in performance increased with distance.

For Select2 (see section 1.7 for full list of common terms), we found instances whereby MT was quicker under both haptic conditions. Shown in Table 4.2 for SelectSM, SelectMM and SelectML, the average MT to task completion under NoF conditions compared to selection with haptic feedback was less by 0.251 seconds, 0.847 seconds and 1.681 seconds respectively. When selecting targets under HtF conditions, MT was quicker for the other three distance combinations: SelectSS, by 0.262 seconds; SelectSL, by 2.094 seconds; and SelectLL, by 3.156 seconds. The standard deviation results also showed performance differences between haptic conditions, in particular for targets placed within the medium and large distance ranges. Other interesting observations included smaller MT for SelectMM with respect to SelectM. In total, these results represent a mixed set of performances. Unlike Select1, when selecting targets with a large displacement, haptic feedback led to better MT results.

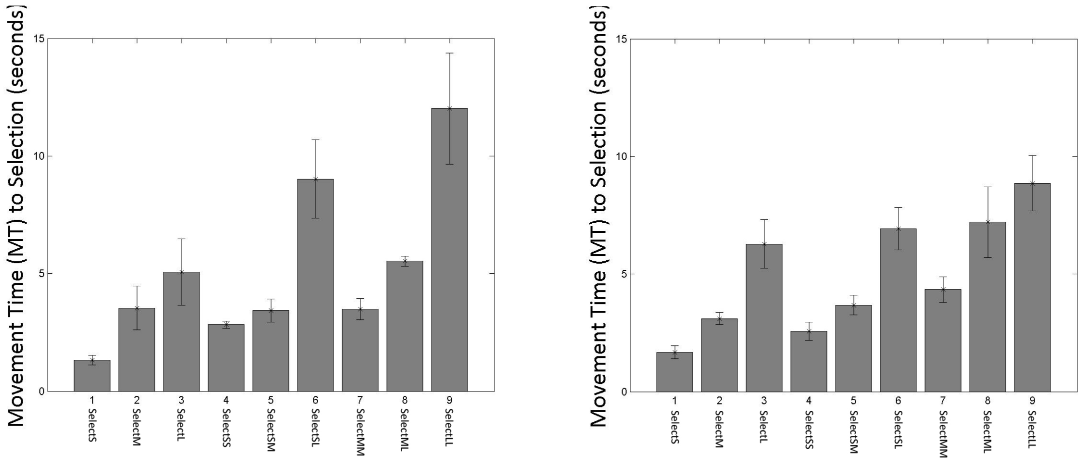
By computing a set of ANOVA results, we investigated the significance of the observed differences in MT between haptic conditions. In Table 4.2, for Select1, the difference in MT between selection with or without haptic feedback was not significant, resulting in p values greater than 0.05 for all distance combinations. This was also true when selecting two targets at SelectSS and SelectSM. However, for SelectSL and SelectLL, the difference in MT under best performing haptic feedback conditions resulted in p values less than 0.05. We also found this result for SelectMM and SelectML whereby selection without haptic feedback achieved quicker MT to task completion. Therefore, this suggests that haptic feedback improved but also hindered MT performance when selecting two targets. When moving to select a single target, haptic feedback did not significantly affect MT to task completion.

4.6.3.2 Distance Travelled (DT)

For Select1, DT results were smaller under no force feedback conditions. Shown in Figure 4.7, for SelectS and SelectL, the average DT was less under NoF conditions compared to selection with haptic force feedback. From Table 4.3, this difference in performance for SelectS and SelectL was 0.320m and 1.747m respectively. In contrast, for SelectM, participants achieved better DT results with haptic feedback by 0.236m. Other observations included larger standard deviation results when selecting targets with haptic feedback. These findings suggest that selection with haptic feedback was detrimental to DT performance, especially with targets with a large displacement from the participant.

When selecting two targets, participants on average used less DT under haptic feedback conditions. Shown in Figure 4.7, this trend was evident when selecting targets placed in the medium and large distance ranges. From Table 4.3, the difference in DT when selecting targets under HtF conditions compared to selection without haptic feedback for SelectSL, SelectMM, SelectML and SelectLL was less by 3.056m, 0.180m, 3.177m and 4.976m respectively. Conversely, for SelectSS and SelectSM DT performance was smaller when selecting targets without haptic feedback. Other observations included smaller standard deviation results for SelectSM, SelectMM, SelectML and SelectLL under haptic feedback conditions. Therefore, unlike Select1, we found that haptic feedback benefited DT performance when selecting targets with either medium or large displacements from the participant.

From the ANOVA results, the observed differences in DT between haptic feedback conditions were significant. From Table 4.3, for SelectL and SelectSM DT performance under NoF conditions was less than selection with haptic feedback achieving p values less than 0.05. This trend was also true for SelectSL, SelectML and SelectLL whereby HtF conditions achieved less DT compared to selection without haptic force feedback. For SelectS, SelectM, SelectSS and SelectMM, the differences in DT between haptic feedback conditions were not significant with p values greater than 0.05. These results demonstrate a trade-off in DT performance between target displacement, number of targets to select and haptic feedback responses.

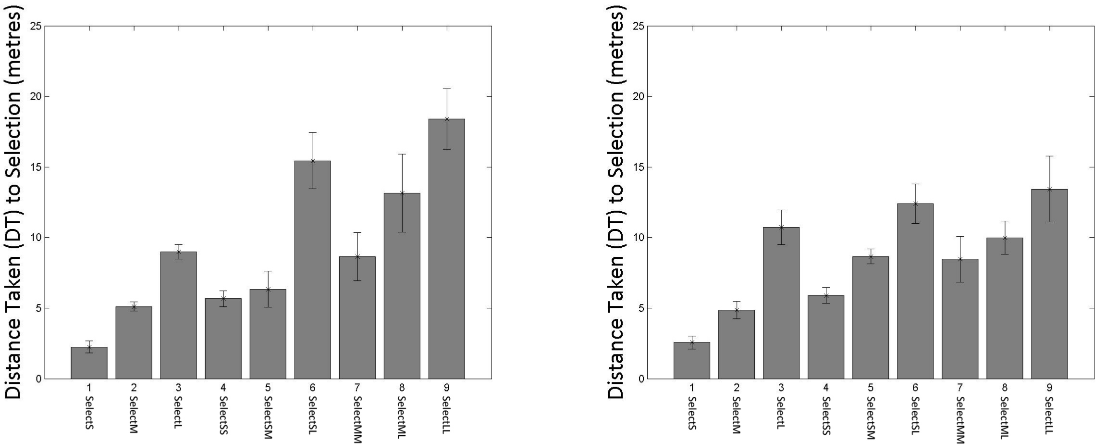


(a) MT- NoF conditions (b) MT- Htf conditions

Figure 4.6: Linear Arm Extension technique (L-AE), Average MT to task completion

Table 4.2: Linear arm extension technique (L-AE), Average MT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	1.317	0.204	1.670	0.278	0.051	5.245
SelectM	3.539	0.926	3.108	0.257	0.345	1.006
SelectL	5.063	1.413	6.282	1.030	0.157	2.433
SelectSS	2.831	0.152	2.569	0.396	0.205	1.907
SelectSM	3.427	0.488	3.678	0.419	0.408	0.762
SelectSL	9.024	1.673	6.930	0.893	0.039	6.091
SelectMM	3.497	0.451	4.344	0.546	0.028	7.166
SelectML	5.530	0.219	7.211	1.505	0.039	6.106
SelectLL	12.016	2.361	8.860	1.173	0.028	7.167



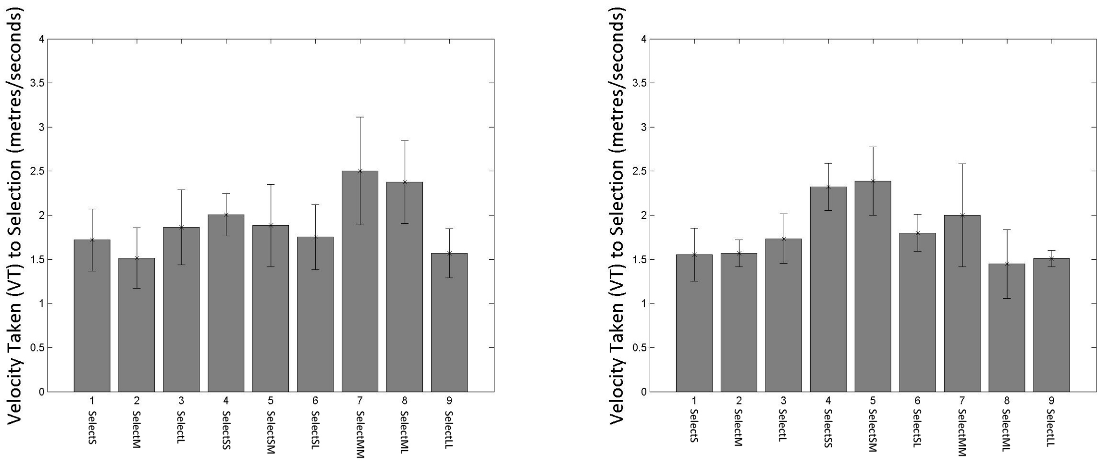
(a) DT- NoF conditions

(b) DT- Htf conditions

Figure 4.7: Linear Arm Extension technique (L-AE), Average DT to task completion

Table 4.3: Linear arm extension technique (L-AE), Average DT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results))

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combinations:						
SelectS	2.240	0.428	2.560	0.459	0.287	1.300
SelectM	5.110	0.320	4.874	0.615	0.469	0.579
SelectL	8.975	0.507	10.722	1.239	0.019	8.520
SelectSS	5.669	0.566	5.895	0.555	0.542	0.406
SelectSM	6.335	1.275	8.657	0.522	0.006	14.204
SelectSL	15.448	1.998	12.392	1.407	0.023	7.821
SelectMM	8.646	1.712	8.466	1.613	0.868	0.029
SelectML	13.159	2.766	9.982	1.173	0.046	5.588
SelectLL	18.401	2.141	13.425	2.334	0.008	12.341



(a) VT- NoF conditions

(b) VT- Htf conditions

Figure 4.8: Linear Arm Extension technique (L-AE), Average VT to task completion

Table 4.4: Linear arm extension technique (L-AE), Average VT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	1.721	0.353	1.554	0.301	0.445	0.647
SelectM	1.515	0.345	1.568	0.152	0.763	0.097
SelectL	1.864	0.425	1.733	0.281	0.582	0.329
SelectSS	2.008	0.240	2.321	0.266	0.087	3.800
SelectSM	1.883	0.468	2.387	0.387	0.101	3.435
SelectSL	1.753	0.370	2.072	0.363	0.810	0.062
SelectMM	2.502	0.610	2.000	0.583	0.220	1.773
SelectML	2.377	0.471	1.447	0.391	0.009	11.539
SelectLL	1.568	0.277	1.715	0.215	0.673	0.192

4.6.3.3 Velocity Taken (VT)

We found variations in VT performance when selecting a single target between haptic feedback conditions. Shown in Table 4.4, the average VT for SelectS, SelectM and SelectL under no force feedback conditions was 1.721m/s, 1.515m/s and 1.864m/s respectively. VT under haptic feedback conditions for SelectS was 1.554m/s; SelectM, 1.568m/s; and SelectL, 1.733m/s. For both feedback conditions, VT performance was larger at SelectL compared to SelectS and SelectM. This suggests that participants when selecting targets under NoF conditions with a larger displacement were able to maintain greater velocity towards selection.

For Select1, VT to task completion was quicker when selecting targets without haptic feedback. From Table 4.4, for SelectS and SelectL, the average VT under NoF conditions compared to selection with haptic force feedback was faster by 0.167m/s and 0.131m/s respectively. For SelectM, VT was faster with haptic feedback by 0.053m/s. Other observations included lower standard deviation results under haptic feedback conditions. These findings indicate that whilst participants were able to select a single target faster under NoF conditions, the variability in performance was greater.

When selecting two targets, the average VT to task completion was best with haptic feedback for the majority of distance combinations. Shown in Figure 4.8, this was evident for all distance combinations except for SelectMM and SelectML. From Table 4.4, for SelectSS, SelectSM, SelectSL and SelectLL the difference in VT under HtF conditions compared to selection without haptic feedback was quicker by 0.313m/s, 0.438m/s, 0.319m/s and 0.147m/s respectively. Again standard deviation results were smaller when selecting targets with haptic feedback. This suggests an interesting interaction between haptic feedback and target displacement, whereby selection at small and large distances VT performance was faster under haptic feedback conditions.

From the ANOVA results, for the majority of distance combinations the observed differences in VT between haptic feedback conditions were not significant. From Table 4.4, except of SelectML, we found that all comparisons between haptic feedback conditions led to p values greater than 0.05. As a result, this demonstrates that haptic feedback had a minimal effect on VT performance when selecting a single and two targets.

4.6.3.4 Observation Summary

Below are a set of summaries describing the movement behaviour when selecting targets for each distance combination. Based upon the notes taken by the experimenter, we highlight the strategies taken to task completion. We also outline the differences in selection performance by comparing the observations for each haptic feedback condition.

- *SelectS*- For both haptic force feedback conditions, participants took a single trajectory to task completion. This was done with little use of corrective movements. Occasionally, we observed instances where the 3D haptic contact points would be moved beyond the target object. At this point, a small backward movement was then used to correct the trajectory and complete the task.

- *SelectM*- Under both haptic conditions participants used a single movement to selection. Overshooting was more evident at this distance range compared to SelectS, whereby participants found it difficult to select targets and correct their movements in a controlled manner. In these circumstances, participants appeared to correct their movements better under conditions with haptic force feedback. Under NoF conditions corrective movements were erratic.

- *SelectL*- Participants found it difficult to select a single target placed in the large distance range. In particular, overshooting was common. Also extra time was spent correcting the movement to compensate for the initial error. For both haptic feedback conditions, we observed an interesting 'sweeping' gesture being used. This involved moving backwards and forwards as if blindly searching to find the target. As a result, we observed uncontrolled movements when moving to select the target in the final phases of movement, increasing the path size to task completion.

  When selecting targets under NoF conditions, participants moved towards the large distance range unimpeded by other surrounding objects. In contrast, under haptic force feedback conditions participants had to negotiate around these obstacles that provided a physical response. Whilst this initially led to a larger path taken for SelectL, participants often used the feedback from the surrounding objects as reference points to then move into the target object in a more controlled fashion. Therefore, under haptic feedback conditions, sweeping gestures were less common.

- *SelectSS*- For both selection with and without haptic feedback, participants selected the yellow then red target using single movements to complete the task. We observed an initial movement to select the first target, then a slight pause before moving onto the next object using single trajectory paths often without overshooting or correction.

- *SelectSM*- Similar to SelectSS, participants were able to select both targets using single trajectory paths without overshooting. Occasionally, participants would manoeuvre their trajectories to avoid surrounding objects that provided a physical resistance. In contrast, under no feedback conditions, movements were more direct passing through obstacles as they did not provide resistance.

- *SelectSL*- For both feedback conditions, selection to the first yellow target was successful as observed with SelectS. However, longer pauses were taken before moving to select the second target placed in the large distance range. For the most part, participants had difficulty selecting the second target. Rather than use a controlled movement to selection, sweeping gestures were used to target the final red sphere.

  For movements to the second target, we noticed differences in selection strategies between haptic feedback conditions. Similar to SelectL, under haptic feedback conditions participants would move around surrounding objects. In contrast, under NoF conditions more direct paths were taken when moving towards the large distance range. However, when nearing the target object, less erratic sweeping gestures were used under haptic force feedback conditions reducing the overall size of the path taken to task completion.

- *SelectMM* - Participants used controlled movements to select targets placed in the medium distance range. As with SelectSS, after selecting the first target we noticed a pause before moving to complete the task. We also observed overshooting and then correcting of the trajectories to select the second target. These movements were done in a controlled manner. These selection strategies were evident for both haptic feedback conditions.

- *SelectML*- Selection to the first target was done in a controlled fashion similar to SelectMM. However, when moving to the large distance range, participants found it difficult to target the final object. Again, we observed sweeping gestures to complete the task and select the last object especially when under NoF conditions. As a result, when selecting targets that provided no feedback participants spent more effort achieving task completion.

  When selecting targets that provided haptic feedback, participants took paths to avoid surrounding objects. Nevertheless movements to the second target were more controlled, often using these obstacles as anchor points. This meant less sweeping gestures were used as found under no haptic feedback conditions.

- *SelectLL*- Participants found it difficult to complete the task for each haptic condition. Sweeping gestures were used to select both targets. This gave the impression that participants used uncontrolled movements to complete the task. When selecting targets without haptic feedback, the initial movements were more direct. However, participants still found it difficult to select targets at this distance. Under haptic feedback conditions, participants took avoiding movements around obstacles. These objects were also used as anchors which limited the use of sweeping gestures. As a result, this led to smaller paths taken to task completion.

For all distance combinations and haptic feedback conditions, participants used both hands to select targets. Predominantly, they would use their dominate hand first to complete the task. If this became difficult, they would use their non-dominate hand, working in co-operation to complete the task.

4.6.4 Results- Non-linear Arm Extension (NL-AE)

4.6.4.1 Movement Time (MT)

For Select1, the average MT to task completion was quicker under no force feedback conditions. Shown in Figure 4.9, this was evident for all 3 distance combinations. From Table 4.5, the difference in MT under NoF conditions compared to selection with haptic feedback for SelectS, SelectM and SelectL was less by 0.253 seconds, 0.098 seconds and 1.460 seconds respectively. Standard deviation results were also smaller for SelectS and SelectL under NoF conditions. Other interesting results included large standard deviation results for SelectL under both haptic feedback conditions. These findings indicate that selection with no force feedback was beneficial to MT performance. Furthermore, when using a non-linear arm extension technique the variability in MT performance was large when selecting targets far away from the participant.

When selecting two targets, smaller MT results were achieved under no force feedback conditions for the majority of distance combinations. Shown in Figure 4.9, except for SelectSS and SelectLL, we found that the average MT to task completion was less under NoF conditions compared to selection with haptic feedback. From Table 4.5, this difference in MT performance for SelectSM, SelectSL, SelectMM, and SelectML was 0.208 seconds, 1.589 seconds, 1.264 seconds and 0.306 seconds. Conversely, when selecting targets with haptic feedback, MT results were less for SelectSS by 0.400 seconds and SelectLL by 0.602 seconds. Standard deviation results for SelectSS, SelectSL and SelectLL were smaller under haptic feedback conditions. Similar to Select1, for both haptic feedback conditions standard deviation results were high, greater than 2.813 seconds when selecting targets placed within the medium and large distance ranges. As a result, this suggests that no force feedback conditions achieved smaller MT results.

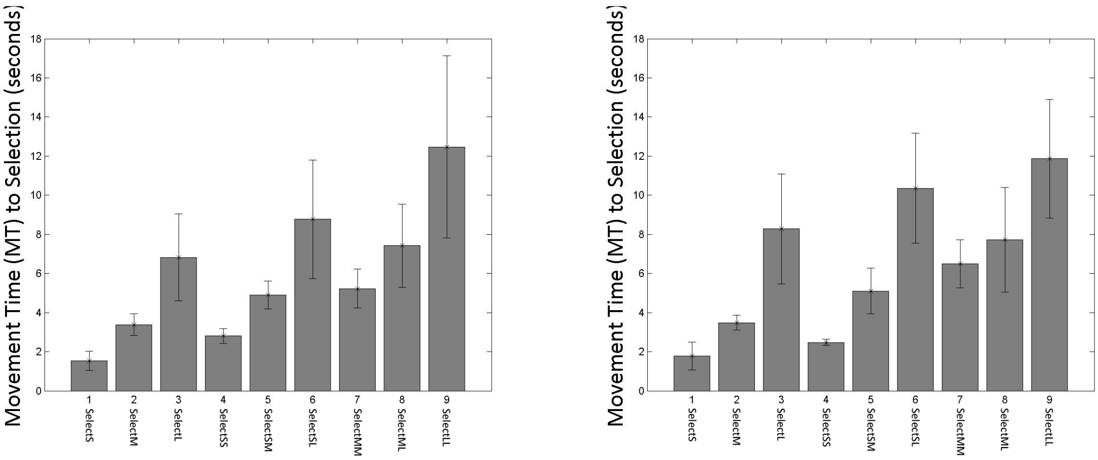
By analysing the ANOVA results, we found that the observed differences in MT between haptic conditions for both selection of one and two targets were not significant. From Table 4.5, differences in MT when selecting targets with and without haptic feedback for all distance combinations achieved p values greater than 0.05. Furthermore, due to the large standard deviation results, this suggests that participants found it difficult using a non-linear arm extension technique when selecting targets placed in the medium and large distance range.

4.6.4.2 Distance Travelled (DT)

Participants on average selected a single target with less DT under haptic feedback conditions. From Table 4.6, the average DT results for SelectS, SelectM and SelectL under HtF conditions compared to selection without haptic feedback were less by 0.700m, 1.073m and 1.985m respectively. Shown in Figure 4.10, we also found that the standard deviation when selecting targets with haptic feedback was smaller. Whilst comparisons between haptic conditions for SelectS were similar, by SelectM and SelectL the standard deviation under NoF conditions was double in size to results achieved with haptic feedback. Therefore, this indicates that DT performance was better when selecting targets with haptic feedback especially over medium and large distance ranges.

When selecting two targets, the average DT to task completion was less under haptic feedback conditions. Compared to results under no feedback conditions, DT performance for SelectSL, SelectMM, SelectML and SelectLL was less by 0.903m, 6.128m, 9.163m and 6.936m respectively. From Table 4.6, we also found that the standard deviation when selecting targets with haptic feedback was smaller compared to selection without haptic responses. As a result, these observations suggest that haptic feedback benefited DT performance by reducing the length of paths taken to task completion and improving consistency.

By computing a set of ANOVA results, this indicated that the differences in DT between haptic feedback conditions were significant. Shown in Table 4.6, for all distance combinations expect for SelectS and SelectSS, DT performance when selecting targets with haptic feedback achieved significantly better results with p values less than 0.05. This demonstrates that participants were able to select targets using trajectories with less size under haptic force feedback conditions when using a non-linear arm extension technique.



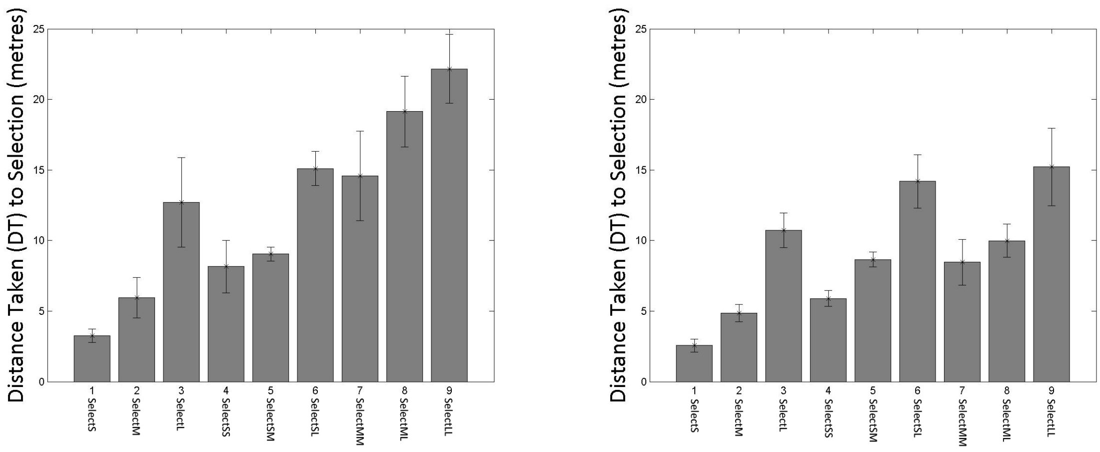
(a) MT- NoF conditions

(b) MT- HtF conditions

Figure 4.9: Non-linear arm extension technique (NL-AE), Average MT to task completion

Table 4.5: Non-linear arm extension technique (NL-AE), Average MT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	1.534	0.498	1.787	0.716	0.534	0.422
SelectM	3.382	0.557	3.480	0.378	0.755	0.104
SelectL	6.825	2.230	8.285	2.811	0.390	0.827
SelectSS	2.805	0.380	2.480	0.148	0.113	3.166
SelectSM	4.897	0.709	5.105	1.159	0.741	0.118
SelectSL	8.768	3.027	10.357	2.813	0.415	0.740
SelectMM	5.229	0.994	6.493	1.224	0.111	3.213
SelectML	7.419	2.133	7.725	2.680	0.847	0.040
SelectLL	12.471	4.659	11.869	3.029	0.815	0.059



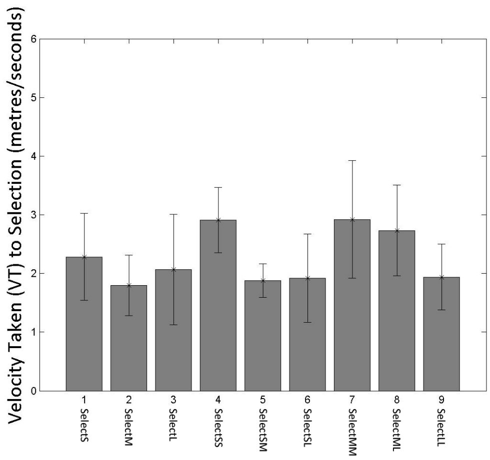
(a) DT- NoF conditions

(b) DT- HtF conditions

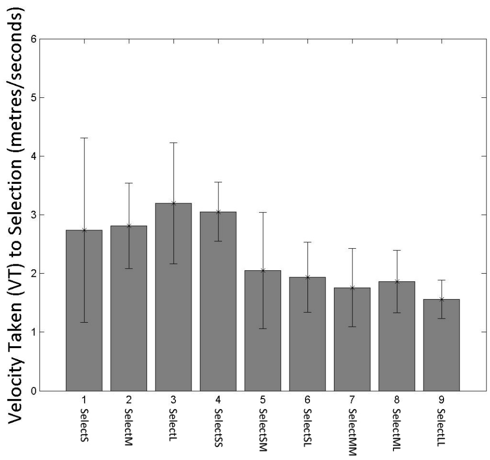
Figure 4.10: Non-linear arm extension technique (NL-AE), Average DT to task completion

Table 4.6: Non-linear arm extension technique (NL-AE), Average DT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	3.260	0.487	2.560	0.459	0.272	1.391
SelectM	5.947	1.425	4.874	0.615	0.027	7.371
SelectL	12.707	3.181	10.722	1.239	0.000	40.244
SelectSS	8.153	1.843	5.895	0.555	0.560	0.370
SelectSM	9.041	0.506	8.657	0.522	0.605	0.289
SelectSL	15.096	1.210	14.193	1.885	0.018	8.881
SelectMM	14.594	3.174	8.466	1.613	0.081	3.987
SelectML	19.145	2.504	9.982	1.173	0.001	24.831
SelectLL	22.161	2.445	15.225	2.745	0.010	11.200



(a) VT- NoF conditions



(b) VT- HtF conditions

Figure 4.11: Non-linear arm extension technique (NL-AE), Average VT to task completion

Table 4.7: Non-linear arm extension technique (NL-AE), Average VT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	2.281	0.740	2.738	1.574	0.572	0.346
SelectM	1.796	0.516	2.813	0.728	0.034	6.505
SelectL	2.066	0.942	3.197	1.032	0.108	3.270
SelectSS	2.907	0.557	3.049	0.503	0.684	0.179
SelectSM	1.878	0.288	2.048	0.990	0.721	0.137
SelectSL	1.922	0.754	1.936	0.600	0.974	0.001
SelectMM	2.921	1.002	1.759	0.666	0.063	4.669
SelectML	2.734	0.771	1.863	0.535	0.072	4.307
SelectLL	1.937	0.560	1.560	0.327	0.229	1.694

4.6.4.3 Velocity Taken (VT)

For Select1 the quickest VT results were achieved when selecting targets with haptic feedback. Shown in Figure 4.11, for all 3 distance combinations, the average VT was greater when selecting targets that provided haptic feedback. From Table 4.7 this difference in VT between results under HtF conditions compared to selection without haptic feedback for SelectS, SelectM and SelectL were greater by 0.457m/s, 1.017m/s and 1.131 m/s respectively. Conversly, standard deviation results were smaller when selecting targets without haptic feedback for all three distance combinations. Therefore, these results indicated that participants were able to select targets with greater velocity with haptic feedback.

When selecting with two targets, we found instances where VT performances were quicker for both selection with and without haptic feedback. From Figure 4.11 for targets placed in the small distance target the average VT was quicker under haptic feedback conditions. In contrast, for medium and large distance combinations VT was quicker when selecting targets without haptic feedback. From Table 4.7, SelectSS, SelectSM, and SelectSL VT performance was best with haptic feedback. In contrast, for SelectMM, SelectML and SelectLL, selection without haptic feedback resulted in better VT performances. Other observations included larger standard deviation results under NoF conditions compared to selection with haptic feedback for SelectMM, SelectML and SelectML. This suggests that participants found it difficult to select targets placed in the medium and large distance ranges without haptic feedback. Altogether, these results demonstrate changes in VT performance between distance and haptic feedback condition.

From the ANOVA results, for Select1 and Select2 the VT differences between feedback conditions were not significant. From Table 4.7, for all distance combinations, comparisons between haptic feedback conditions lead to p values greater than 0.05. Therefore, whilst selection with haptic feedback led to quicker results, the difference was not significant to suggest that haptic feedback did not affect VT performance when using a non-linear arm extension technique.

4.6.4.4 Observation Summary

Below are a set of summaries describing the movement behaviour for each distance combination. With respect to handedness, we found similar strategies used when using a linear arm extension technique.

- *SelectS*- For both haptic force feedback conditions, participants took a single trajectory to task completion. At times, we observed instances where the 3D haptic contact points would move beyond the target object. Upon this event, participants took corrective measures.

- *SelectM*- Under both haptic conditions, participants used a single movement to selection. Unlike SelectS, overshooting was more evident whereby participants found it difficult to select targets and correct their movements in a controlled manner. In these circumstances participants appeared to correct their movements better when selecting targets that provided haptic feedback upon selection.

- *SelectL*- Participants found it difficult to select target placed in the large distance range. Overshooting was common and extra time was spent correcting the initial error. For both haptic feedback conditions, we observed sweeping gestures used after moving within a nearby proximity of the target object. This led to uncontrolled movements within the large distance range.

When selecting targets that did not provide haptic feedback, participants moved towards the large distance range unimpeded by other objects. In contrast, under haptic force feedback conditions participants had to negotiate around obstacles that provided resistance. As a result, larger paths were taken to task completion.

- *SelectSS*- For both selection with and without haptic feedback, participants selected the yellow then red target using single movements to complete the task. We observed an initial movement to select the first target, then a slight pause before moving onto the next object using a trajectory with limited correction. At times, participants found it difficult making small movements often overshooting the second target. Again, this was characterised by a sweeping gesture when selecting the final target.

- *SelectSM*- Participants found it difficult to select both targets at either distance range. In particular, movements between targets were uncontrolled. Furthermore, selection behaviours were different between feedback conditions, especially upon contact and the subsequent trajectories to the final target. Often when selecting without haptic feedback participants would move through the first target unimpeded to then overshoot the final target. Conversely, when selecting targets with haptic feedback, participants would select the first target but then pause creating two distinct movement phases. Again, for both haptic conditions we found overshooting and sweeping gestures being used to select the final target.

- *SelectSL*- Similar to SelectSM, selection behaviour was different between both haptic force feedback conditions. When selecting targets without haptic feedback, participants often moved through the first target and other surrounding objects. As a result, after selecting the first target, movements to the second were more continuous. In contrast, when selecting targets with haptic feedback, participants would pause upon selection and then make a second distinct movement to the last target. For both haptic feedback conditions, overshooting occurred in addition to the use of sweeping gestures to select the final target. Nevertheless, when selecting targets that provided feedback, participants would try to use the other objects as reference points reducing the need for sweeping gestures in the large distance range.

- *SelectMM*- Again participants struggled to select both targets. For both haptic feedback conditions, overshooting was common and erratic motions to task completion. When moving beyond a target, corrective movements led to further errors. Similar to the other distance combinations, different selection strategies were used between haptic feedback conditions. Under NoF conditions, participants could select and move through targets and obstacles resulting in a smoother path to task completion. In contrast, when selecting targets providing feedback, there were distinct movements between collisions with targets and other obstacles. In some cases, participants would use

Table 4.8: Linear and non-linear arm extension- Summary of significant results between haptic conditions for each task difficulty ('x' indicates conditions with significant differences between haptic conditions)

	L-AE			NL-AE		
	MT	DT	VT	MT	DT	VT
SelectS						
SelectM					x	x
SelectL		x			x	
SelectSS						
SelectSM		x				
SelectSL	x	x			x	
SelectMM	x					
SelectML	x	x	x		x	
SelectLL	x	x			x	

obstacle targets to rest and then move slowly to the target object. This reduced overshooting and the need for corrective movements.

- *SelectML*- Again participants struggled to select targets at this distance range. In terms of behaviours this was similar to those observed for SelectMM.

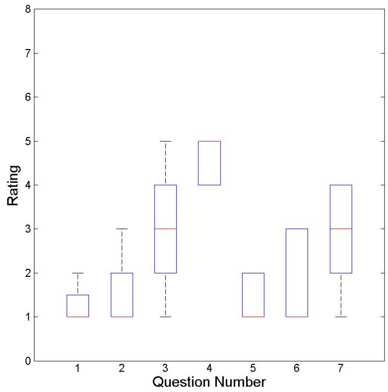
- *SelectLL*- For both targets, participants found it difficult to select targets in the large distance range. Sweeping gestures were used to select and move to both targets giving the impression of uncontrolled movements to achieve the task. In particular, participants found it very difficult to correct their movements at the large distance range. When selecting targets without haptic feedback, participants were able to move freely and through obstacles using a more direct path to task completion. However, when selecting both targets sweeping gestures were used. For haptic feedback conditions, participants had to avoid targets that provided resistance. This led to additional movements away from the target objects. Also corrective movements were hard to perform leading to overshooting and the use of sweeping gestures. Nevertheless, by being able to collide with other obstacles these were used as anchor points to then move on to the final target.

4.6.5 Discussion

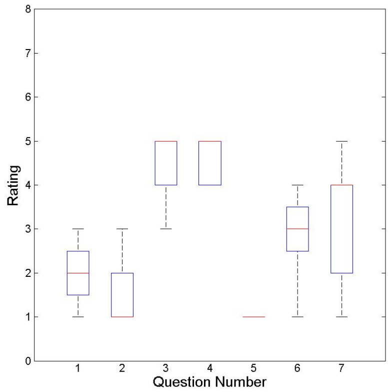
From the collected results, we were able to identify certain selection strategies participants used to select targets when using a linear and non-linear arm technique. Based upon the recorded MT, DT and VT performance markers, we were able to describe changes in user selection depending on the type of haptic feedback condition rendered. Summarised in Table 4.8, we also highlighted how these strategies were affected by the number and target displacement.

Linear arm extension technique:

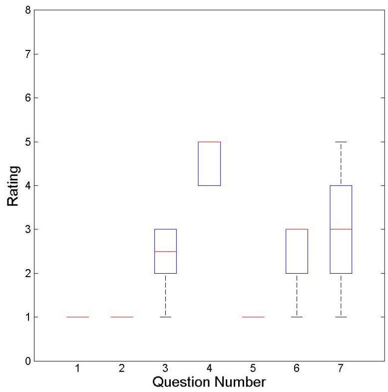
- When selecting a single target, we found that haptic force feedback provided no significant benefit



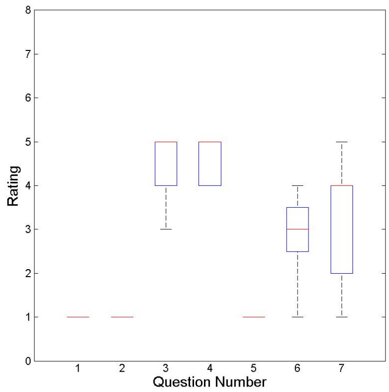
(a) Linear arm extension- NoF conditions



(b) Linear arm extension- Htf conditions



(c) Non-linear arm extension- NoF conditions



(d) Non-linear arm extension- Htf conditions

Figure 4.12: linear and non-linear arm extension usability questionnaire results: Questions 1) Was the interaction technique easy to use? (1=Hard to use, 5=Easy to use) 2) Did the interaction feel natural? (1=Not natural, 5=Natural) 3) Was the interaction responsive? (1=Not responsive, 5=Responsive) 4) Did you feel sick? (1=Sick, 5=Normal) 5) Did you experience any delay of feedback? (1=Small, 5=Large) 6) How would you rate the interaction technique? (1=Bad, 5=Good) 7) How would you rate presented tasks? (1=Hard, 5=Easy)

to MT or VT performance. However, when selecting targets far away, haptic force feedback had a detrimental effect on DT performance resulting in larger paths to task completion. As described in the observation summaries, this change in selection behaviour was a consequence of participants having to move around objects that provided a physical resistance. This behaviour was also evident under NoF conditions, but to a lesser extent as participants were able to move through objects that provided no physical resistance thus leading to shorter DT results. This is an interesting finding, indicating that objects with haptic feedback provide a natural barrier to performance when selecting targets.

- In contrast, the display of haptic force feedback benefited the selection of two targets with respect to MT and DT. For selection with and without haptic feedback, overshooting errors were common especially when moving towards targets placed far away. To correct these errors, participants used sweeping gestures which led to an increase in DT to select the second target. However, when selecting targets that provided haptic feedback, participants were able to use this physical interaction with the surrounding obstacles to correct their movement at distance better, resulting in more efficient paths taken to task completion. This suggests that when performing more complex tasks, haptic feedback can be used to improve performance.

Non-Linear arm extension technique:

- For both selection of one or two targets, we did not find any significant differences in MT and VT performance between selection with and without haptic feedback. Nevertheless, the least DT to task completion was achieved when selecting targets that provided haptic feedback.
- For each haptic condition, we found large standard deviation results indicating participants were unable to select targets in a consistent manner. As described by the observation summaries, participants found it difficult to correct their trajectories especially with targets placed far away due to the large displacements in movement at distance. Some benefit to DT was provided when selecting targets with haptic feedback as obstacles were used as physical reference points to stabilise movement when in the large distance range. However, the variability of these results increased with distance. In general, participants found it difficult to selection targets using a non-linear arm extension technique.

When comparing the results from the two arm extension techniques, we found that participants had difficulty controlling a non-linear transfer function when selecting targets at distance. As shown in the usability results in Figure 4.12, participants found the interaction technique was hard to use, which in turn made the selection task more difficult to complete. This was also reflected by participants rating a non-linear arm extension technique harder and less natural to use compared to a linear arm extension technique.

Interestingly, due to this extra difficulty, we found that the effects observed when selecting targets with haptic feedback using a linear arm extension technique did not apply to the non-linear case. In particular, when using a non-linear arm extension this led to participants unable to control the extra gain in extension in all axes. As noted in the observation summaries, in this instance overshooting targets placed far away from the participant was more common resulting in poor performance. This indicates that whilst haptic feedback can help when selecting multiple targets placed far away, the extent to this benefit can be limited by the lack of control.

For both linear and non-linear arm extension techniques, we identified different ways in which haptic feedback affected selection performance. Furthermore, we found that the selection strategies to a single target were different to those used when acquiring two targets. In particular, we also found that the selection strategies used changed depending on haptic condition. This is an interesting result, suggesting that the strategies used for selecting a single target with haptic feedback do not necessarily transfer for multiple targets. We can also conclude that the selection of multiple targets with haptic feedback is not a composition of individual single selection tasks, whereby the presentation of subsequent targets may influence movement to the first target.

To summarise, we found that:

- When selecting targets placed far away, haptic feedback was a natural barrier to DT performance as participants have to move around, or take longer paths by moving around objects to complete the task.
- Under NoF conditions, participants would also avoid potential obstacles to task completion but to a lesser extent. Participants would often go through objects that provided no resistances to movement to select the intended target, thus taking a more direct path.
- When selecting multiple targets placed over medium to long distances, haptic feedback can be used to overcome the difficulty of these tasks.
- Sweeping and searching gestures were used when participants were unable to use visual or haptic feedback to select targets placed far away.
- The use of a non-linear arm extension gain function was deemed too hard to use, thus resulting in poor selection performance.

4.7 Experiment II: Velocity Based Travel Selection Techniques (VBT)

In this experiment, we evaluated the performance of two types of velocity based travel techniques when selecting targets with and without haptic force feedback. To continue our user study in section 4.6, we used the same IVE experiment to capture a set of measures defining selection performance with targets placed a different displacements from the user. To define two types of movement characteristics within the IVE we implemented a linear and non-linear transfer function. By using pilot studies, we tailored the parameters of these functions to the connected hardware. With this setup and the collected data sets, we highlight instances whereby haptic feedback either helped or hindered selection performance when using a velocity based travel technique.

4.7.1 Implementation of Velocity Based Travel Selection Technique

Rather than extend to a 3D object, travel techniques move the cursor throughout the virtual workspace whilst maintaining the initial relationship between the user's body and their interaction points. Within haptic simulations, some form of viewpoint control is common: either using a separate device or an alternate mode of one or more haptic devices that also control the camera but not the interaction point [Tho01]. By using this technique, we enabled participants to reposition their viewpoint using the GRAB arms to bring distant objects within arm's reach for selection.

Based upon the characteristics of the GRAB arms, we implemented a velocity based travel technique whereby participants could manoeuvre their viewpoint based upon in the direction of their extended arms. Shown in Figure 4.13, movements up/down, left/right, forwards and backwards, represented positional changes to the viewpoint in the x, y and z axis respectively. For example, to initiate a translation towards a target, participants moved their hands beyond 3/4 length of the GRAB devices workspace for each axis. When at this limit, we applied a velocity function moving the 3D haptic contact points and the viewpoint together in the direction of the hand gesture. The velocity gain function was controlled by the participant moving their arm's and the GRAB interface forward within an activation area, whereby full extension achieved maximum velocity and the minimum gain set when entering this space.

Shown in Figure 4.13, throughout the travel process, we always maintained the initial positional relationship between the participant's viewpoint and cursor. Once a velocity function was activated, we repositioned both the 3D haptic contact points and viewpoint using the same vector in real-time. By doing so, participants were able to use the same hand gestures when selecting object positioned within arm's reach to those placed far away.

We defined the velocity transfer functions based upon pilot studies with expert users. As with the evaluation of an arm extension technique, we implemented a linear and non-linear transfer function defining the velocity control. Below are the defined parameters providing suitable locomotion between targets without being too fast not to impact the coordinate required to select targets. For both transfer functions, their activation only occurred at 3/4 length of the GRAB workspace in each dimension.

Linear Velocity Control:

We set the maximum extension ratios to 4:1, 4:1, 4:1 for the x, y and z axes respectively.

$$x_d = 4x_{hp} \tag{4.7}$$

$$x_{dp} = 4x_{hp} \tag{4.8}$$

$$y_d = 4y_{hp} \tag{4.9}$$

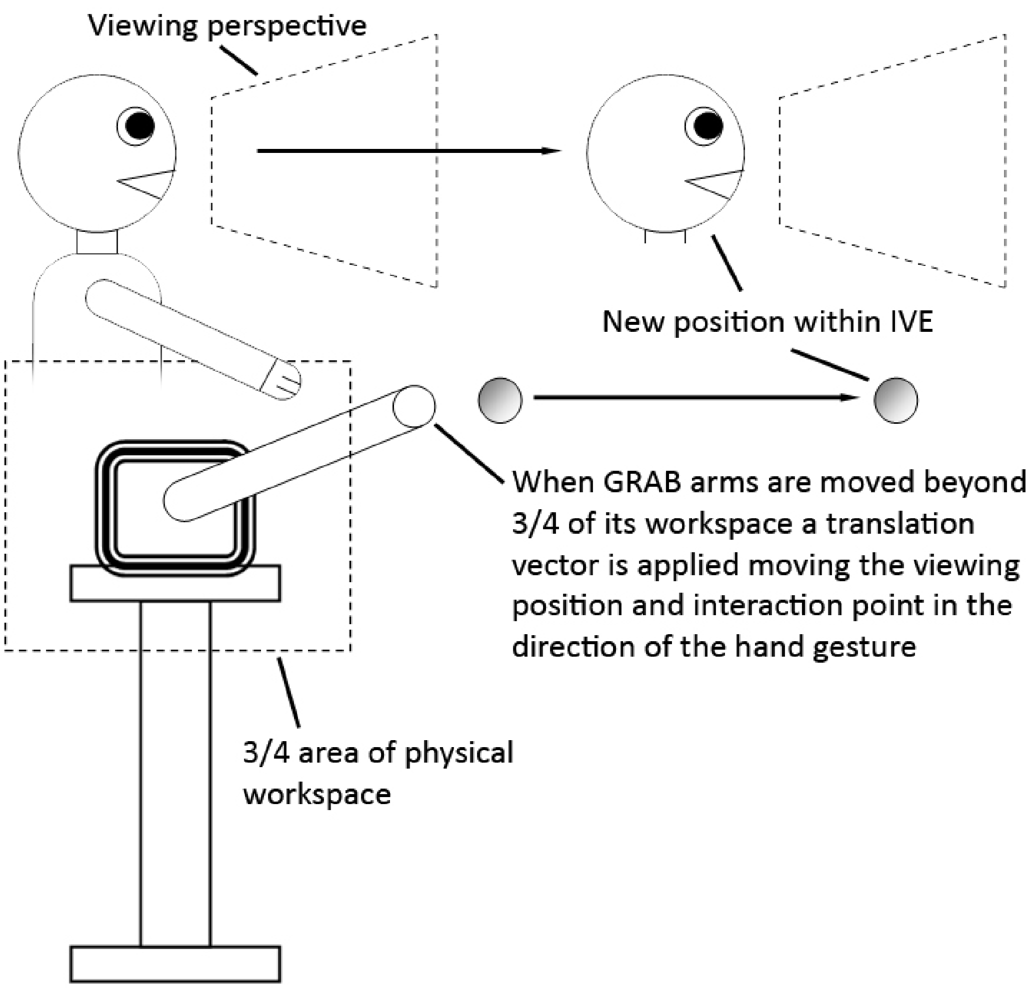


Figure 4.13: Design of velocity based travel interaction technique

$$y_{dp} = 4y_{hp} \tag{4.10}$$

$$z_d = 4z_{hp} \tag{4.11}$$

$$z_{dp} = 4z_{hp} \tag{4.12}$$

- x_d, y_d, z_d- new displacement of 3D haptic points.
- x_{dp}, y_{dp}, z_{dp}- new displacement of viewpoint in IVE.
- x_{hp}, y_{hp}, z_{hp}- displacement of the haptic arms.

Non-linear Velocity Control:

A exponential transfer function was implemented to translate the haptic contact point to the limits of the extended workspace. We used the same velocity ratios for each axis as used for a linear velocity control. Again, this was only activated when GRAB arms were at 3/4 length in each dimension.

$$x_v = 1.17^{x_{hp}} \tag{4.13}$$

$$x_{vp} = 1.17^{x_{hp}} \tag{4.14}$$

$$y_v = 1.17^{y_{hp}} \tag{4.15}$$

$$y_{vp} = 1.17^{y_{hp}} \tag{4.16}$$

$$z_v = 1.17^{z_{hp}} \tag{4.17}$$

$$z_{vp} = 1.17^{z_{hp}} \tag{4.18}$$

- x_v, y_v, z_v- new displacement of 3D haptic points.
- x_{vp}, y_{vp}, z_{vp}- new displacement of viewpoint in IVE.
- x_{hp}, y_{hp}, z_{hp}- displacement of the haptic arms.

4.7.2 Experiment Procedure and Participants

We evaluated 40 participants (32 male and 8 female), 20 for each of the two implemented velocity based travel techniques. For each trial, each participant selected targets using both velocity based travel techniques but with only one haptic condition. To reduce any carry-over effects the presentation order of the selection techniques were randomised. Before starting the experiment, each participant was given a pre-questionnaire outlining general guidelines and the context of the work (see Appendix A). A breakdown of the participants is given in Table 1 (see Appendix A).

We asked general background information indicating that all the participants were right handed and had a 'good' experience of 3D games equivalent to 10 hours or above playing video games per week. In terms of the demographic of the participants, they were taken from members of the Department of Computer Science at University College London and post-graduate students. 16 participants had previously used the ReaCToR and GRAB arms.

Before starting the experiment we gave each participant a demonstration of the equipment and a thorough induction. Each participant had 10-15 minutes to accustom themselves with the GRAB haptic interface, ReaCToR, head tracking and the presented interaction technique under both haptic conditions to level out any learning effects. Once done, we repeated the instructions, answered any questions, and asked if the participant was ready to start the experiment.

Once started, we logged measurements during the experiment. The experimenter also maintained a discrete observation post and kept notes of the behaviour of each participant describing the strategies taken to complete the selection tasks. After completion, every participant was given a 15 minute break and then asked to fill a usability questionnaire for the velocity based travel technique. When finished, another 5 minute break was given before starting the remaining velocity based travel technique.

Again, we gave full instructions before starting the final experiment condition. Another set of the same usability questionnaires were also given at the end. In total, the experiment lasted 1 hour and each participant was compensated with a monetary reward at the end.

Similar to the design used to evaluate the two arm extension techniques, we used a between subjects design to evaluate the different haptic conditions. This was done so that we could evaluate multiple variables at once. Due to this design consideration it was important that we performed the experiments with a large number of participants. No explicit instructions were given to complete the tasks as quickly or accurately as possible. Though participants were asked to complete the tasks by selecting the targets in the correct order.

Again, to clarify, as the experiment was designed to be a series of repetitive tasks thinking time was not independently evaluated. Also, at the start of each trial we included 15 selection tasks that we discounted in the results, as to eliminate the learning effects on the data of the participants at the start the experiment. When participants made false movements, defined as selecting targets in the wrong order, this was logged by the experimenter and excluded from the results. Nevertheless, all other movements were included.

4.7.3 Results - Linear Velocity Based Travel (L-VBT)

4.7.3.1 Movement Time (MT)

When moving to select a single target, selection under no force feedback conditions achieved quicker MT results to task completion. From Table 4.9, we found that the average MT under NoF conditions compared to selection with haptic feedback for SelectS, SelectM and SelectL was quicker by 0.125

seconds, 1.008 seconds and 1.738 seconds respectively. Standard deviation results were also smaller under no force feedback conditions except for SelectL. This suggests that MT performance was best when selecting targets that did not provide feedback upon contact.

For Select2, no force feedback conditions achieved quicker MT results. Shown in Figure 4.14, for all distance combinations the average MT to task complete was smaller under NoF conditions. From Table 4.9, this difference in MT between NoF conditions compared to selection with haptic feedback for SelectSS, SelectSM, SelectSL, SelectMM, SelectML and SelectLL was quicker by 0.190 seconds, 0.062 seconds, 0.225 seconds, 2.941 seconds, 1.366 seconds, 0.888 seconds and 1.733 seconds respectively. Standard deviation results were also smaller when selecting targets under NoF conditions. Therefore, these results show that selecting targets under no force feedback conditions led to quicker MT performances.

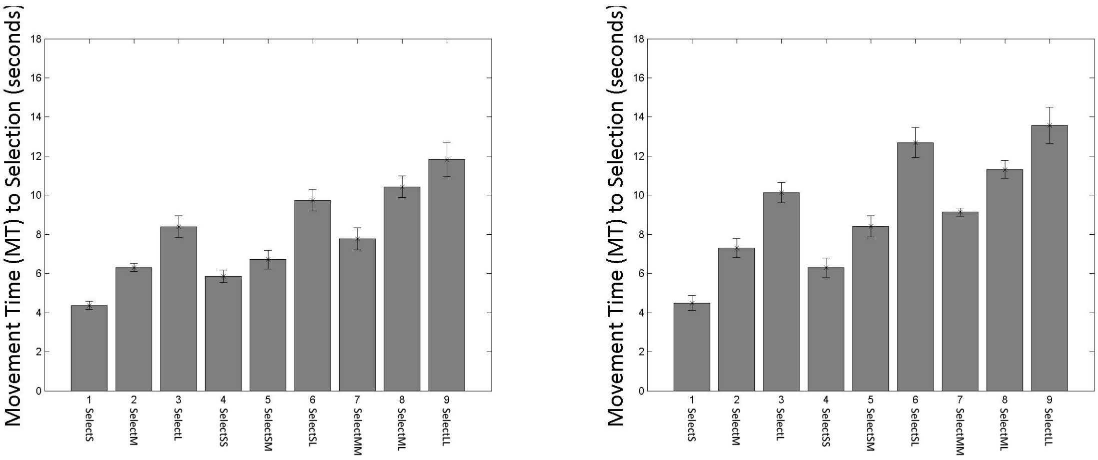
By analysing the ANOVA results, we found that the observed differences in MT between haptic feedback conditions was significant. From Table 4.9, excluding results for SelectS and SelectSS, for all other distance combinations the difference in MT under best performing NoF conditions compared to selection with haptic feedback lead to p values less than 0.05. This demonstrates that MT performance was best without haptic feedback when using a linear based velocity travel technique to select targets placed beyond the small distance range.

4.7.3.2 Distance Travelled (DT)

For Select1, selection without haptic feedback resulted in shorter DT results to task completion. Shown in Figure 4.15, the average DT to task completion under NoF conditions was shorter for all three distance combinations. From Table 4.10, this difference in DT under NoF conditions compared to selection with haptic feedback for SelectS, SelectM and SelectL was smaller by 0.135m, 0.230m and 1.274m respectively. Conversely, standard deviation results were smaller under haptic feedback conditions except for SelectS. Therefore, this indicates that whilst participants took shorter paths to task completion under no feedback conditions, the variability in performance was greater.

When selecting two targets, the shortest DT to task completion was achieved under no force feedback conditions. Shown in Figure 4.15 this trend was evident when moving to select targets placed in either the medium or large distance ranges. From Table 4.10 the difference in average DT under NoF conditions compared to selection with haptic feedback for SelectSL, SelectMM, SelectML and SelectLL was smaller by 2.369m, 2.162m, 1.398m and 1.668m respectively. Conversely, DT under HtF conditions was shorter for SelectSS by 0.259m and SelectSM by 0.156m. Standard deviation results were smaller under NoF conditions for SelectSS, SelectML and SelectML. Whereas for SelectSM, SelectSL and SelectMM standard deviation results were smaller under HtF conditions. Again, these findings suggest that selection without haptic feedback improved DT performance except when targets were placed in the small distance range.

By computing a set of ANOVA results, we found that the difference in DT when selecting targets without haptic feedback was significant. From Table 4.10, we found for SelectL, SelectSL, SelectMM, SelectML and SelectLL selection without haptic feedback achieved shorter DT results with p values less



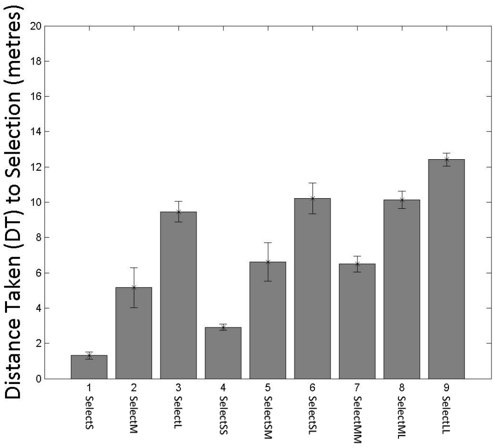
(a) MT- NoF conditions

(b) MT- HtF conditions

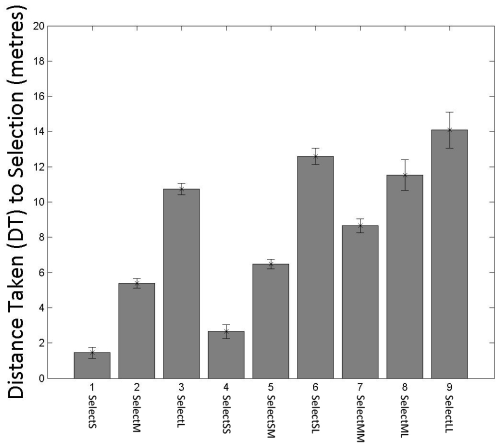
Figure 4.14: Linear velocity based travel (L-VBT), Average MT to task completion

Table 4.9: Linear velocity based travel (L-VBT), Average MT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	4.369	0.216	4.494	0.377	0.538	0.414
SelectM	6.306	0.202	7.314	0.494	0.003	17.867
SelectL	8.394	0.559	10.132	0.522	0.001	25.834
SelectSS	5.854	0.317	6.293	0.507	0.139	2.701
SelectSM	6.705	0.475	8.402	0.537	0.001	28.003
SelectSL	9.746	0.547	12.687	0.772	0.000	48.356
SelectMM	7.771	0.567	9.137	0.214	0.001	25.399
SelectML	10.426	0.551	11.314	0.451	0.024	7.775
SelectLL	11.829	0.872	13.562	0.936	0.016	9.177



(a) DT- NoF conditions

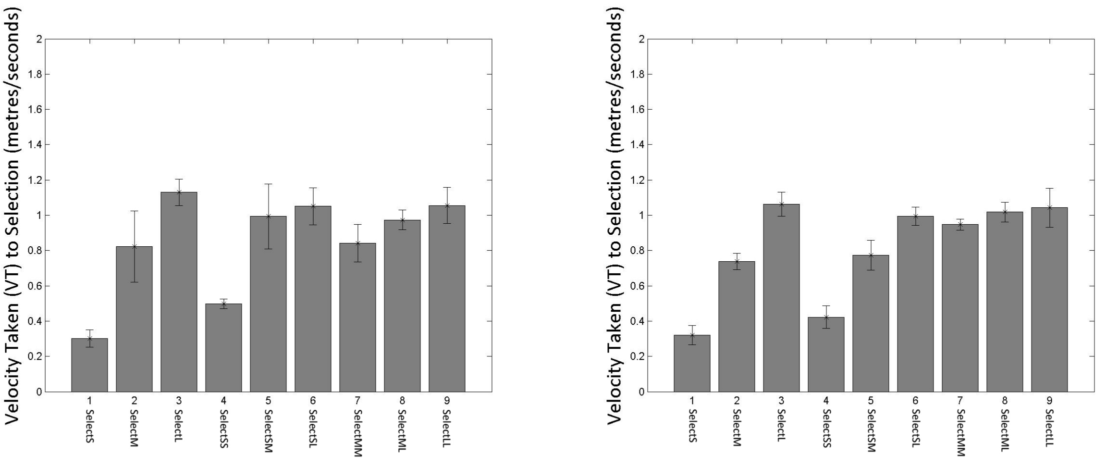


(b) DT- HtF conditions

Figure 4.15: Linear velocity based travel (L-VBT), Average DT to task completion

Table 4.10: Linear velocity based travel (L-VBT), Average DT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	1.317	0.204	1.452	0.308	0.439	0.663
SelectM	5.159	1.136	5.389	0.270	0.672	0.193
SelectL	9.463	0.582	10.737	0.321	0.003	18.385
SelectSS	2.911	0.175	2.652	0.402	0.223	1.746
SelectSM	6.627	1.093	6.471	0.269	0.764	0.097
SelectSL	10.224	0.873	12.593	0.461	0.001	28.813
SelectMM	6.497	0.451	8.659	0.393	0.000	65.274
SelectML	10.130	0.488	11.528	0.861	0.013	9.979
SelectLL	12.416	0.362	14.084	1.0175	0.009	11.923



(a) VT- NoF conditions

(b) VT- HtF conditions

Figure 4.16: Linear velocity based travel (L-VBT), Average VT to task completion

Table 4.11: Linear velocity based travel (L-VBT), Average VT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	0.302	0.049	0.322	0.055	0.562	0.366
SelectM	0.823	0.202	0.739	0.046	0.390	0.825
SelectL	1.130	0.076	1.062	0.068	0.175	2.220
SelectSS	0.498	0.027	0.423	0.063	0.041	5.936
SelectSM	0.994	0.184	0.774	0.084	0.042	5.870
SelectSL	1.052	0.105	0.995	0.053	0.312	1.166
SelectMM	0.842	0.106	0.948	0.031	0.065	4.592
SelectML	0.973	0.056	1.019	0.056	0.235	1.650
SelectLL	1.056	0.102	1.043	0.110	0.856	0.035

than 0.05. In contrast, comparisons between haptic feedback conditions for SelectS, SelectM, SelectSS and SelectSM lead to p values greater than 0.05. This shows that when using a linear velocity based travel technique, selection without haptic feedback improved DT performance when selecting targets in the medium and large distance ranges.

4.7.3.3 Velocity Taken (VT)

For Select1, participants completed the task with the largest average VT under no feedback conditions. Shown in Figure 4.16, this was for targets placed in the medium and large distance ranges. From Table 4.11, the average VT for SelectM and SelectL under NoF conditions compared to selection with haptic feedback was greater by 0.084m/s and 0.068 m/s respectively. Conversely, selection with haptic feedback achieved faster VT results for SelectSS by 0.020 m/s. Standard deviation results were smaller when selecting targets with haptic feedback for SelectM and SelectL. These results suggest that the average VT to task completion was larger without haptic feedback, but led to greater variability in performance.

When selecting two targets, we found that VT performance was quicker under no feedback conditions. Except for SelectMM and SelectML, the average VT to task completion was larger when selecting targets that did not provide any feedback upon contact. Shown in Table 4.11, this difference in VT for SelectSS, SelectSM, SelectSL and SelectLL was 0.075m/s, 0.220m/s, 0.057m/s and 0.013m/s respectively. Conversely, standard deviation results were larger under NoF conditions for all distance combinations except for SelectSS and SelectLL. These results suggest that no haptic feedback conditions improved VT performance.

From the ANOVA results, we found that the observed differences in VT between haptic feedback conditions were not significant. From Table 4.11, expect for distance combinations SelectSS and SelectSM, comparisons between haptic feedback conditions lead to p values greater than 0.05. As a result, this indicated that selection without haptic feedback led to better VT performances only for targets placed within small and medium distance ranges.

4.7.3.4 Observation Summary

Below are a set of summaries describing the selection behaviour observed when using a linear velocity travel technique. In terms of handedness, participants traversed the distance ranges using their dominate hand. They also used the same hand to select the intended target. The other hand was rarely used. This behaviour was observed for all distance combinations.

- *SelectS*- For both haptic force feedback conditions, we found no difference in the strategies used to select the target. Participants did not overshoot when moving to select the target and were able to make small corrective motions to task completion.

- *SelectM*- Similar to SelectS, when selecting targets under both haptic feedback conditions participants used a single movement to selection. Occasionally, when navigating targets that provided haptic feedback participants would take avoiding movements around obstacles. Under no feedback conditions, more direct paths were taken moving through obstacles.

- *SelectL*- As with SelectS and SelectM, we did not find any significant differences in the selection strategies used between the different feedback conditions assessed. Under haptic feedback conditions, participants moved the 3D haptic points to avoid other obstacles and take longer sized paths to task completion. Conversely, when selecting targets that provided no force feedback, more direct paths to task completion were taken. However, similar to SelectM these differences were small and participants were able to select the single target in one movement without overshooting.

- *SelectSS*- For both selection with and without haptic feedback, participants selected the yellow then red target using single movements to task completion. Small variations in movement was observed upon selection whereby when selecting targets without haptic feedback, participants were able to push through the yellow target and move on the second target without stopping or correcting their path. When selecting targets that provided feedback, upon selection of the first target, participants would stop then move around the target and select the second target. This difference meant that under no feedback conditions participants were able to maintain their velocity throughout the task.

- *SelectSM*- Similar to SelectSS, participants were able to select both targets using a single trajectory path without overshooting. Again, when selecting targets without haptic feedback, participants often went through the first target without stopping to then move to the second target.

- *SelectSL*- For both feedback conditions, selection to the first yellow target was successful as observed with SelectS. However, we observed changes in the trajectory and movement from the first target to the second between feedback conditions. Under haptic feedback conditions, participants would stop and move around targets that provided feedback. In contrast, when under no feedback conditions, when moving to the second target participants move through the first target taking a more direct line to complete the task. Additionally, when selecting targets that provided feedback, participants would correct their path to avoid obstacles. This behaviour was less evident under no feedback conditions.

- *SelectMM*- Participants used controlled movements to select targets placed in the medium distance range. Again, whilst trajectories between targets were similar between feedback conditions, we found differences in the selection behaviour upon collision. As a result, when moving without haptic feedback, participants were able to select the first target without changing their trajectory to the second target.

- *SelectML*- Similar to SelectSL, we observed differences in the trajectories taken to the large distance area and behaviour upon contact between feedback conditions. Under no feedback conditions participants were able to push through the first target and move to the second unimpeded. As a result, less avoiding trajectories were taken when navigating between obstacles in comparison to selection with haptic feedback.

- *SelectLL*- Selection behaviour was similar to that observed for SelectSL, SelectMM and SelectML.

4.7.4 Results - Non-Linear Velocity Based Travel (NL-VBT)

4.7.4.1 Movement Time (MT)

When selecting a single target, MT was quicker under haptic feedback conditions. Shown in Figure 4.17, this trend was evident for small and medium distance ranges. From Table 4.12, the average MT results for SelectS and SelectM under haptic feedback conditions were faster by 0.263 second and 0.219 seconds respectively. Nevertheless, when selecting a target placed in the large distance range, we found MT performance to be smaller without haptic feedback by 0.530 seconds. With respect to the standard deviation results, selection with haptic feedback achieved larger results especially for SelectM. These results suggest a trade-off in MT between distance and haptic feedback conditions, whereby participants performed better when selecting targets placed in the small distance range and that provided a physical response.

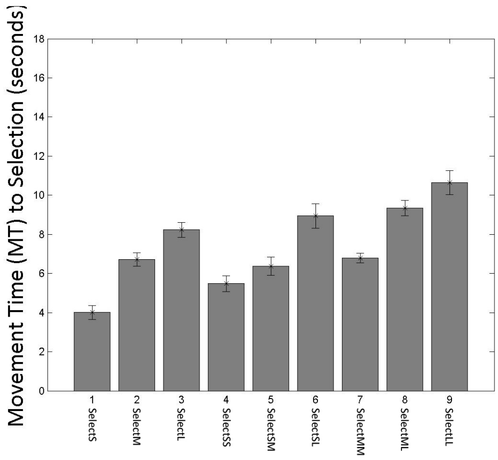
For Select2, we found that no force feedback conditions lead to smaller MT results. Shown in Figure 4.17, this occurred for all distance combinations except for SelectSS. From Table 4.12, the average MT to task completion under NoF conditions compared to selection with haptic feedback for SelectSM, SelectSL, SelectMM, SelectML and SelectLL was quicker by 1.928 seconds, 2.107 seconds, 1.181 seconds, 1.105 seconds and 1.100 seconds respectively. Other observations included changes in smaller standard deviation results between haptic feedback conditions and distance combination. These findings demonstrate that selection without haptic feedback improved MT performance.

By analysing these trends further, we found that the observed MT differences when selecting a single target between feedback conditions were not significant. However, this was not true when selecting two targets. From Table 4.12, all comparisons between feedback conditions and distance combinations except for SelectSS achieved p values less than 0.05. Therefore, this suggests when selecting two targets with haptic force feedback this led to quicker MT results to task completion when using a non-linear velocity based travel technique.

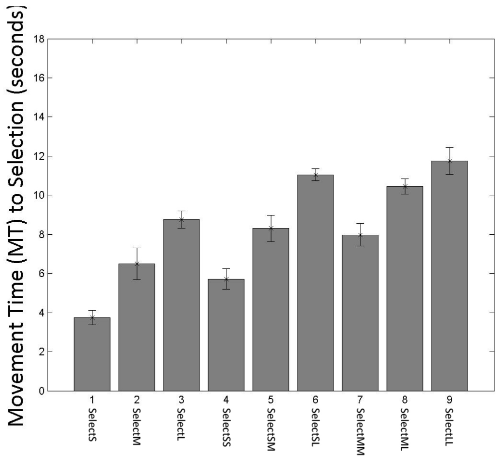
4.7.4.2 Distance Travelled (DT)

When selecting a single target participants took the least DT to task completion without haptic feedback conditions. In Figure 4.18, this trend was evident for all distance combinations. From Table 4.13, the average DT to task completion under NoF conditions compared to selection with haptic feedback for SelectS, SelectM and SelectL was smaller by 0.135m, 0.230m and 1.274m respectively. Conversely standard deviation results were larger under no force feedback conditions for all distance combinations. This indicated that selection without haptic feedback led to shorter DT results, but with greater variability in performance.

For selection of two targets, selection without haptic feedback lead to smaller DT results. Shown in Figure 4.18, the average DT to task completion under NoF conditions was smaller for all distance combinations except for SelectSS and SelectSM. From Table 4.13, the difference in DT under NoF conditions compared to selection with haptic feedback for SelectSL, SelectMM, SelectML and SelectLL was 2.369m, 2.180m, 1.398m and 1.668m respectively. Conversely, standard deviation results were larger for NoF conditions except for SelectSS, SelectML and SelectLL. Therefore, these results suggest



(a) MT- NoF conditions

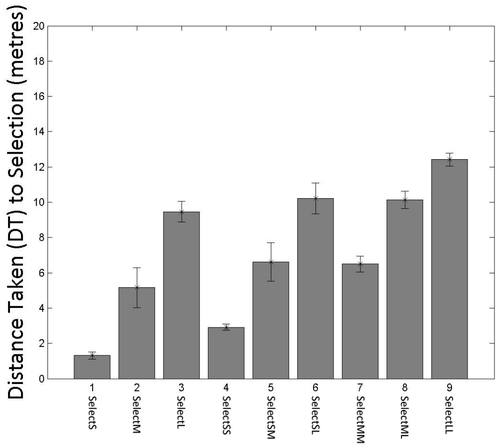


(b) MT- HtF conditions

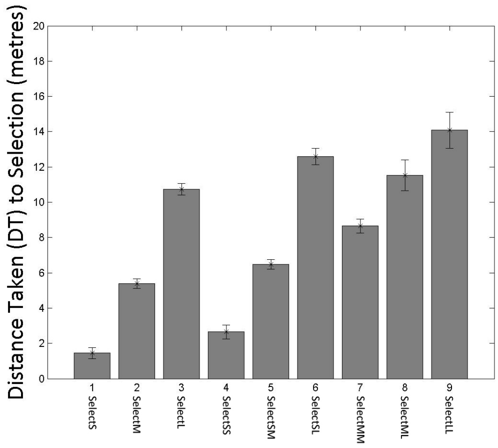
Figure 4.17: Non-linear velocity based travel (NL-VBT), Average MT to task completion

Table 4.12: Non-linear velocity based travel (NL-VBT), Average MT and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	4.006	0.358	3.743	0.365	0.282	1.331
SelectM	6.708	0.340	6.489	0.810	0.592	0.312
SelectL	8.229	0.377	8.759	0.446	0.077	4.132
SelectSS	5.476	0.416	5.716	0.533	0.450	0.630
SelectSM	6.381	0.469	8.309	0.678	0.001	27.350
SelectSL	8.939	0.637	11.046	0.312	0.000	44.121
SelectMM	6.794	0.250	7.975	0.573	0.003	17.867
SelectML	9.343	0.404	10.448	0.386	0.002	19.608
SelectLL	10.646	0.623	11.746	0.693	0.030	6.958



(a) DT- NoF conditions

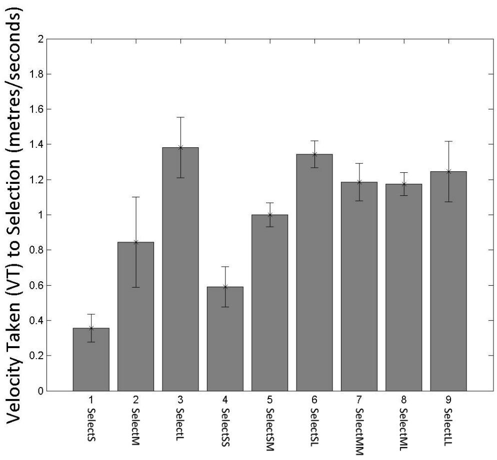


(b) DT- HtF conditions

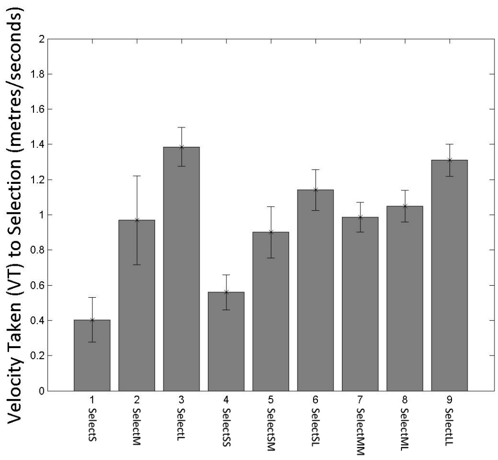
Figure 4.18: Non-linear velocity based travel (NL-VBT), Average DT to task completion

Table 4.13: Non-linear velocity based travel (NL-VBT), Average DT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combinations:						
SelectS	1.317	0.204	1.452	0.308	0.811	0.061
SelectM	5.159	1.136	5.389	0.270	0.558	0.374
SelectL	9.463	0.582	10.737	0.321	0.316	1.145
SelectSS	2.911	0.175	2.652	0.402	0.902	0.016
SelectSM	6.627	1.093	6.471	0.269	0.035	6.449
SelectSL	10.224	0.873	12.593	0.461	0.359	0.946
SelectMM	6.497	0.451	8.659	0.393	0.576	0.340
SelectML	10.130	0.488	11.528	0.861	0.957	0.003
SelectLL	12.416	0.362	14.084	1.018	0.027	7.250



(a) VT- NoF conditions



(b) VT- HtF conditions

Figure 4.19: Non-linear velocity based travel (NL-VBT), Average VT to task completion

Table 4.14: Non-linear velocity based travel (NL-VBT), Average VT, standard deviation and ANOVA results for each distance combination between haptic feedback conditions (n=20 for each haptic condition, and highlighted text indicate significant results)

Feedback combination:	NoF		HtF		NoF vs HtF	
	Average	Std	Average	Std	p - value	f - value
Distance combination:						
SelectS	0.356	0.078	0.404	0.126	0.491	0.522
SelectM	0.845	0.257	0.969	0.253	0.463	0.593
SelectL	1.383	0.172	1.386	0.111	0.979	0.001
SelectSS	0.591	0.115	0.560	0.101	0.657	0.213
SelectSM	1.000	0.069	0.901	0.146	0.209	1.869
SelectSL	1.344	0.077	1.141	0.117	0.012	10.558
SelectMM	1.185	0.107	0.986	0.085	0.011	10.689
SelectML	1.174	0.066	1.048	0.089	0.035	6.431
SelectLL	1.246	0.171	1.310	0.092	0.479	0.553

that no force feedback conditions led to shorter DT performances when selecting two targets.

By analysing the ANOVA results, when selecting a single target the difference in DT between haptic condition was not significant. This trend was also evident for Select2. From Table 4.13, the difference in DT for only SelectSM and SelectLL between haptic conditions achieved p values less than 0.05. These findings indicated that haptic force feedback condition did not affect DT performance to task completion when using a non-linear velocity based travel technique.

4.7.4.3 Velocity Taken (VT)

For Select1, VT was quickest under haptic feedback conditions. Shown in Figure 4.19, this was evident for all distance combinations. From Table 4.14, the average VT to task completion under haptic feedback conditions compared to selection with no force feedback for SelectS, SelectM and SelectL was greater by 0.048 m/s, 0.124 m/s and 0.003 m/s. Standard deviation results were also smaller with haptic feedback conditions expect for SelectS. This suggests that selecting targets with haptic feedback improved VT performance.

When selecting two targets, the average VT to task completion was quicker under no force feedback conditions. Shown in Figure 4.19, VT to task completion was larger all distance combinations expect for SelectSS and SelectLL. From Table 4.14, VT under NoF conditions compared to haptic feedback conditions for SelectSM, SelectSL, SelectMM and SelectML was larger by 0.099m/s, 0.203m/s, 0.199m/s and 0.126m/s. Standard deviation results for NoF conditions were less for SelectSM, SelectSL and SelectML. Unlike Select1, this indicated that selection without haptic feedback led to quicker VT performances.

From the ANOVA results, we found that the observed differences in VT for Select1 were not significant. Shown in Table 4.14, all comparisons between feedback conditions and distance combinations achieved p values greater than 0.05. For Select2, VT differences for SelectSL, SelectMM and SelectML achieved p values less 0.05. This suggests that selection with two targets under no feedback conditions improved VT performance for targets placed in the medium and large distance ranges.

4.7.4.4 Observation Summary

Below are a set of summaries describing the selection behaviour observed when using a non-linear velocity travel technique. With respect to handedness, participants traversed the virtual environment using their dominate hand. This behaviour was observed for all distance ranges.

- *SelectS*- For both haptic force feedback conditions, we found no difference in the strategies used to select the target. Participants did not overshoot when moving to select the target and used small corrective motions to task completion. Upon performing a corrective movement, participants would try to reduce the velocity of movement.

- *SelectM*- Similar to SelectS, when selecting targets under both haptic feedback conditions participants used a single movement to selection. We did not observe any changes in behaviour between feedback conditions.

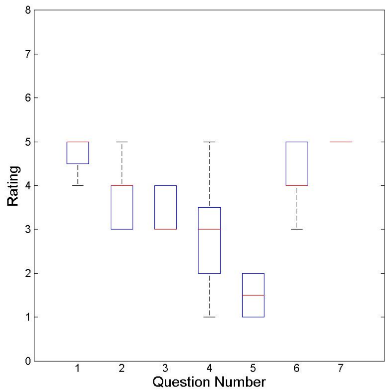
- *SelectL*- As with SelectS and SelectM, we did not find any significant differences in the selection strategies used between the different haptic feedback conditions. Occasionally, under haptic feedback conditions participants took longer paths to task completion by avoiding a collision with other obstacles. However, these differences between haptic feedback condition were small.
- *SelectSS*- For both selection with and without haptic feedback, participants selected the yellow then red target using single movements to the complete the task. Small variations were observed when moving from the yellow to the red target. Under haptic feedback conditions, upon collision with the first target, participants would stop their movement and move around obstacles to then complete the task. When selecting without haptic feedback participants moved directly from the first target to the second without stopping, pushing through targets that were in the way.
- *SelectSM*- Similar to SelectSS, participants were able to select both targets using single trajectory paths without overshooting. Again, when selecting targets without haptic feedback, participants often went through the first target without stopping to then move to the second target.
- *SelectSL*- For both feedback conditions, selection to the first yellow target was successful as observed with selectS. However, we observed changes in the trajectory and movement from the first target to the second between feedback conditions. Under haptic feedback conditions, participants would stop and move around targets that provided feedback. In contrast, when under NoF conditions, participants moved through the first target taking a more direct line to the second target without stopping.
- *SelectMM*- Participants used controlled movements to select targets placed in the medium distance range. Similar to SelectSM, the trajectories taken between targets were difference for each feedback condition. In particular, when moving without haptic feedback, participants were able to select the first target without changing their trajectory to the second target.
- *SelectML*- Similar to SelectSL, we observed differences in the trajectories taken to the large distance area and behaviour upon contact between feedback conditions. Under no feedback conditions participants pushed through the first target to then complete the task. Furthermore, less avoiding trajectories were taken when navigating between obstacles in comparison to selection with haptic feedback.
- *SelectLL*- With respect to haptic feedback conditions, we found differences in the initial selection and trajectories taken. When selecting targets that did not provide haptic feedback, participants were able to push through the first target and maintain their movements to the second target without correction. This was in contrast to selection with haptic feedback whereby participants had to stop and correct their movements to avoid obstacles that provided feedback.

4.7.5 Discussion

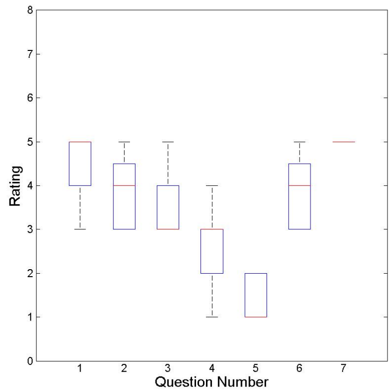
In Table 4.15 we summarised the significant results when using a linear and non-linear velocity based travel technique. Based upon the captured results, we built the following performance profiles:

Table 4.15: Linear and non-linear arm extension- Summary of significant results between haptic conditions for each task difficulty (‘x’ indicates conditions with significant differences between haptic conditions)

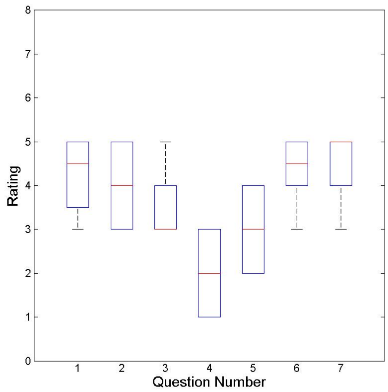
	L-VBT			NL-VBT		
	MT	DT	VT	MT	DT	VT
SelectS						
SelectM	x					
SelectL	x	x				
SelectSS			x			
SelectSM	x		x	x	x	
SelectSL	x	x		x		x
SelectMM	x	x		x		x
SelectML	x	x		x		x
SelectLL	x	x		x		



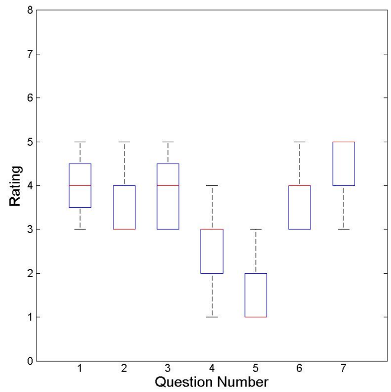
(a) Linear velocity based travel- NoF conditions



(b) Linear velocity based travel- Htf conditions



(c) Non-linear velocity based travel- NoF conditions



(d) Non-linear velocity based travel- Htf conditions

Figure 4.20: linear and non-linear velocity based travel usability questionnaire results: Questions 1) Was the interaction technique easy to use? (1=Hard to use, 5=Easy to use) 2) Did the interaction feel natural? (1=Not natural, 5=Natural) 3) Was the interaction responsive? (1=Not responsive, 5=Responsive) 4) Did you feel sick? (1=Sick, 5=Normal) 5) Did you experience any delay of feedback? (1=Small, 5=Large) 6) How would you rate the interaction technique? (1=Bad, 5=Good) 7) How would you rate presented tasks? (1=Hard, 5=Easy)

Linear velocity based travel technique:

- When selecting a single target, we found that haptic force feedback had a detrimental effect on MT and DT performance over large distances only. When selecting targets over short and medium distances there was no difference in performance between haptic conditions. As described in the observation summaries, haptic feedback changed the selection behaviour whereby participants had to move around objects that provided resistance. This led to participants taking significantly greater paths to complete the task compared to selection without haptic feedback.
- For selection for two targets, the trend for Select1 continued whereby MT and DT performances were best under NoF conditions. With haptic force feedback, participants had to stop and move around objects and other obstacles increasing the effort needed to complete the task. In contrast, selection without haptic feedback meant participants could move through the first target without changing their initial velocity and take a more direct path to selection.
- For both selection with a single and two targets, we found no difference in VT performance between haptic feedback conditions and distance.

Non-linear velocity based travel technique:

- No difference in performance between haptic conditions when selecting a single target.
- Similar to a linear based velocity travel, MT and DT performances was best when selecting targets that did not provide haptic feedback. Again, this was due to participants taking avoiding movements around obstacles resulting in larger paths to task completion.
- For selection of two targets, again MT and DT performance was best under no feedback conditions. When under haptic feedback conditions, participants had to move around and avoid targets that provided resistance. Whereas when selecting targets with no haptic feedback, participants were able to push through unimpeded to tasks completion and achieve better results.
- DT performance under haptic feedback conditions achieved larger standard deviation results indicating participants were unable to select targets in a consistent manner. As described by the observation summaries, participants found it difficult to perform corrective movements using a non-linear velocity based travel technique. VT performance was similar for selection under both haptic feedback conditions.

From the usability results, we found that comparisons between selection with a linear and non-linear velocity based travel technique were similar. Interestingly from Figure 4.20, participants found selection with a linear velocity easier to use than selection with a non-linear transfer function. From the observation summaries, this was because participants found it difficult to accurately correct their movement whilst traversing the IVE.

For both selection techniques, haptic feedback had the same effect on performance. In particular, when selecting targets that provided haptic feedback, this led to larger MT and DT results as extra effort was needed to move around obstacles that acted as a barrier to task completion. This shows that for both velocity based travel techniques, haptic feedback had a detrimental effect on selection performance.

To summarise:

- For both selection techniques, haptic feedback led to participants taking longer paths to task completion when asked to select both a single and multiple targets.
- Participants preferred selection with a linear velocity based travel technique though the difference in performance was small.

4.8 Summary

In this chapter we presented two experiments evaluating different types of distal interaction techniques (sections and 4.6 and 4.7). For both selection with arm extension and velocity based travel techniques, we presented how haptic feedback affected the strategies used when selecting either a single or two targets. As shown by the captured results, we found that haptic feedback affected each interaction technique differently as profiled by changes in MT, DT and VT performance. More specifically, we also observed that selection strategies for a single target were different to when using the same interaction technique to acquire two targets.

From the experiments conducted in chapter 4, the results show the changes in size of paths taken between haptic conditions. For simple tasks, common observations included participants taking longer paths to selection under haptic force feedback conditions. . This was shown by participants having to move around objects that provided a physical response. Nevertheless, haptic feedback was also used to overcome control and stability problems such as providing a physical reference point to move between objects when selecting at a distance. Altogether, the results presented suggest that the strategies used are dependent on the number of targets, the difficulty of the task in addition to the specification of the presented interaction technique. Other interesting observations included evidence of sweeping gestures used to overcome very difficult tasks that were not supported by either the presented visual or haptic cues. For designers of novel interaction techniques within IVEs, these experiments provide useful case studies including the benefits of different combinations of visual and haptic interaction.

In chapter 5, we investigated the effects of haptic feedback using more natural forms of selection. We follow a similar format of evaluation as used in chapter 4, however we improved the data recording procedures to illustrate the trajectories taken to task completion as discussed in 3.4.3. We also updated the testbed experiment design to improve its repeatability.

Chapter 5

Haptic Force Feedback Effects on Natural 3D Selection

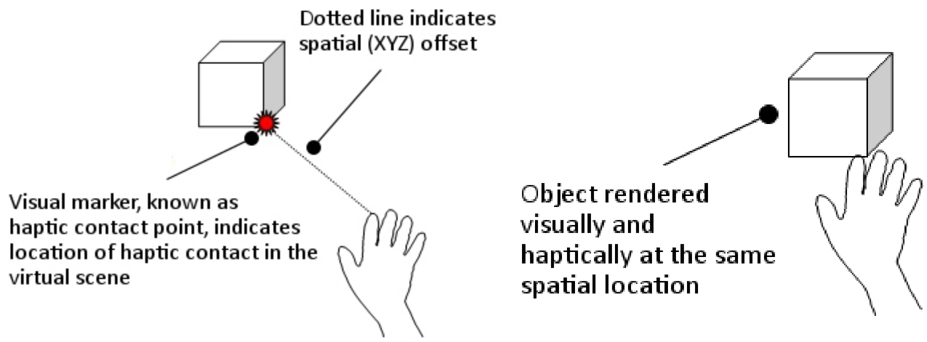
5.1 Overview

In this chapter we investigated the effects of haptic force feedback on a natural 3D selection technique. To do this, we implemented methods to co-locate the displayed visual and haptic cues to a common temporal and spatial domain. By imposing a 1-to-1 alignment, users were able to manoeuvre the 3D haptic contacts and select targets with hand gestures representative to the real world.

Building upon results from chapter 4, we extended the experimental framework to evaluate different types of haptic force feedback conditions on 3D selection performance. Discussed in section 5.5.2, we implemented three types of force feedback responses felt upon contact: hard force feedback, soft force feedback and no force feedback. Furthermore, we also assessed two types of interaction: right hand only and bi-manual interaction. Based upon these different haptic conditions, our user study highlighted different movement strategies taken to select targets when using a natural selection technique.

To segment this chapter, we used the sections below:

- *Natural 3D Selection Technique Design (section 5.2)*- We define the characteristics of natural 3D selection techniques. We also introduce the 'co-location' of visual and haptic cues.
- *Haptic Force Feedback and 3D Selection Performance (section 5.3)*- Outline the current research investigating the effects of haptic feedback on 3D selection when using natural interaction techniques.
- *Experimental Aims and Expectations (section 5.4)*
- *Design of Experimental Framework (section 5.5)*- Description of the IVE experiment used to evaluate user performance. We also describe the implemented natural 3D selection technique.
- *Results- Right Hand Interaction (section 5.6)*- Comparison in selection performance between haptic feedback conditions when using the right hand only to select targets.
- *Results- Two Handed Interaction (section 5.7)*- Comparison in selection performance between haptic feedback conditions when using both hands to select targets.



(a) Distal Interaction (b) Co-located Interaction

Figure 5.1: Differences in design between a distal and co-located visual-haptic interaction technique

5.2 Natural 3D Selection Technique Design

When building natural 3D selection techniques, designers aim to transfer the benefits observed in the real world to the virtual environment. Within IVE platforms, this type of interaction is well supported, allowing for user centric factors such as a large field-of-view, in addition to visual motion and vestibular cues. Designers can also incorporate other basic human factor principles such as two handed interaction thought to be important for natural 3D selection [HPP+97]. A key argument for developing natural interaction techniques is it can enable further participation within the presented IVE [vLM04].

Studies into assembly task design provide examples supporting the use of natural interaction techniques. Described by Petzold et al. direct 3D manipulation and selection requires IVEs that are highly interactive; displaying multiple cues from different sensory modalities [PZF+04]. In particular, work by Zhang demonstrated the benefits of using multimodal display systems to user performance [ZSF05]. As a result, researchers are investigating the use of audio and haptic feedback to build more intuitive methods of interaction and improve task performance [DFM05] [CAL+06] [HACH+04].

When designing multimodal interfaces, it is commonly thought that all input cues should be ‘co-located’. First termed by Wall et al., ‘co-location’ describes a display system where the local coordinate frames of the available sensory input cues coincide [WPS+02]. For example, a sound-producing object should get louder when it visually appears closer, and sound should be perceived to come from the same direction that we see the object. Likewise, for visual-haptic co-location, we should be able to feel the edge of an object at precisely the location where we see that edge. Shown in Figure 5.1, co-located interfaces differ from more typical distal interaction setups in that each of the visual, haptic and auditory input cues are precisely aligned with one another throughout the entire working volume. With this setup, the resultant interaction promotes natural methods of interaction, mirroring the usual configuration of cues similar to the real world.

Within IVE platforms, precise visual and haptic co-location is hard to achieve. Only a few studies using small-scale desktop device have successfully demonstrated this type of interaction model [LMP+07]. Due to these challenges, there is continuing debate regarding the potential performance benefits of co-location. Studies argue that for certain applications this level of complexity may not be necessary [Bie87], [CSH+92], [OS05]. For example, human factor studies by Graham et al. suggest that co-located displays offer no significant advantage [GM96]. Nevertheless, Wall and Rose argue that this experiment was inherently two dimensional, and in turn demonstrated that visual-haptic co-location of the hand in the virtual workspace was helpful in tasks involving object rotation [YRB01]. Expanding this further, Arsenault and Ware showed that correct registration with haptic cues improved user task performance. In contrast, similar studies by Sprague et al., found less obvious results [SPB06], whilst in other scenarios researchers report better depth perception of object shape and detection [JO04].

In general, these studies represent a mixed set of performance results. Validated platforms demonstrating good visual-haptic co-location are not widely available. Furthermore, reusable evaluations that attempt to understand the end user effects when integrating multimodal cues together remain underdeveloped. For example, Dinh et al., reported that inadequate calibration can hinder user perception of visual-haptic environments [DWS+99]. In contrast, Bouguila et al., demonstrated that adaptation to small lateral displacements in the mismatch between visual and haptic cues are rapid and of little consequence, suggesting that haptic feedback can help to overcome instabilities in the user's visual depth perception [BIS00]. Ultimately, due to these conflicting reports and the lack of good evaluation methodologies, it is hard to assess how haptic feedback affects the gestures employed when using natural 3D selection techniques. Therefore, as our hardware set up is novel, results from current studies though informative are not directly transferable.

5.3 Haptic Force Feedback and 3D Selection Performance

As described by Samur et al. the evaluation methodologies used to understand the effects of haptic feedback vary considerably [SWSB07b]. Predominately, current studies focus on either analysing the technical usability of newly developed haptic interfaces, or attempt to define user performance using metrics specific to certain application tasks. Partly due to the infancy of haptic hardware development, work extending beyond device or task specific evaluations is therefore limited. As a result, there is relatively little research developing reusable evaluation methods that measures the influence of haptic feedback on user behaviour when performing generalised tasks such as 3D selection.

Research into 3D interaction within IVEs has introduced numerous methods for 3D object selection. Introduced in section 2.4.3, domain-specific design methods, taxonomies and testbed analysis have all shown to be useful in understanding user performance for distal 3D interaction techniques [CB09] [HCS98] [Han97]. In comparison, when evaluating more natural 3D selection technique designs, the interactions used to assess user performance have typically centred around Fitts' style selection tasks. Within the 2D domain, a vast body of human factor studies exist. For 3D interaction this is much less. Only a few explicitly consider visual-haptic co-location and other user centric factors particular to IVE platforms.

Building upon our discussion in section 2.5.2, Wang and MacKenzie performed an experiment in which subjects moved an object in hand to dock with a 3D wireframe graphic cube [WM00]. Linderman, Sibert and Hahn also compared human performance when docking a graphic object to either a 'floating' graphic panel or to a panel that was augmented by a physical paddle [LSH99]. These studies reported that in conditions with haptic feedback, subjects were faster at docking the object compared to when there was no haptic feedback. Finally, Arsenault and Ware reported movement time advantages when haptic feedback was available upon target contact in a Fitts' style aiming task [AW00b].

Tapping tests are also used to measure human performance in simple target selection tasks. Separate studies by Wall and Oakley, showed that force feedback significantly reduced subjects movement times [WH00] [OMBG00]. Other experimental designs include peg-in-holes tasks [SH05], targeting [CVBS04], haptic training [ASFB02], joint tasks in a shared virtual environment [BHSS00] and object recognition [OG02] tests.

The rendering of hard virtual surfaces is also another common benchmark topic [LPD$^+$00]. Guerraz et al. [Fer08] suggested to use physical data from a haptic device to evaluate the user interface. Kappers et al. [PCKN05] performed haptic identification experiments using quadric surfaces and showed that shape index, a quantity describing the surface structure had significant effect on haptic shape identification. Building upon these studies, Kirkpatrick and Douglas [KD02] produced similar work. They expressed their results in bits of information transfer and showed that humans could correctly identify at most 3 to 4 sphere sizes (corresponding to 2 bits) ranging from 10 to 80mm in radius using the PHANToM. Murray et al. also used an information transfer concept to evaluate their wearable vibrotactile glove [Web78].

Most human factor studies evaluating haptic feedback only offer interaction with one hand. Whilst this is an adequate method of selection, it is thought that strict natural interaction models should include the availability of two hands. Research into bi-manual interaction has become an accepted technique for 'fish tank' 3D manipulation, IVEs, and for 2D interfaces such as ToolGlass [HPP$^+$97]. Studies by Ulinski et al., evaluated four selection techniques for volumetric data based on the four classes of bimanual action: symmetric-synchronous, asymmetric-synchronous, symmetric-asynchronous, and asymmetric-asynchronous [UWG$^+$09]. They suggest that symmetric and synchronous selection strategies both contribute to faster task completion. Nevertheless, due to the expense of incorporating input devices into large IVEs, there is very little research investigating bi-manual 3D selection. Therefore, when evaluating haptic feedback on natural 3D selection, it is important to consider a complete set of user centric factors.

For our own evaluation, by using Fitts' style experimental design we will be able to build upon previous work. Due to the number of influencing factors, from the hardware setup to the design of the selection task, we explicitly define these parameters.

5.4 Experimental Aims and Expectations

Following on from chapter 4, when using a natural interaction technique we expected that the combination of haptic and visual feedback will be superior to visual feedback when using a natural selection technique to acquire a single target (time to touch a single object from a starting position). Our second hypothesis was that this will no longer be true for complex selection tasks because the haptic force feedback will cause the user to take longer or slower paths to targets after selecting the first.

By assessing different types of haptic force feedback, we believed that the strategies taken to acquire a single or multiple targets will be dependent on the stiffness felt upon contact. A formative hypothesis was that the type of haptic feedback rendered would affect the task efficiency when selecting multiple targets, such that the experience of no, soft or hard haptic force feedback cues would result in different paths and effort made to task completion. At this stage, we did not have any prior expectations to which haptic feedback condition would produce better performances with respect to MT, DT and VT. Similarly, we did not have any insights to the gestures employed when using a natural interaction technique.

Ideally within IVEs we wish to always support unbiased two handed selection. However, in many facilities there is often a constraint, such as only one hand-tracker or one force feedback device being available. Thus we ran both single (right), and two handed trials with the expectation that bi-manual interaction would be superior to selecting targets with only the right hand. To scope the work, we only studied virtual hand techniques with no view point traversal. Therefore, the user could only select objects they wish to touch within their arm's length.

5.5 Design of Experimental Framework

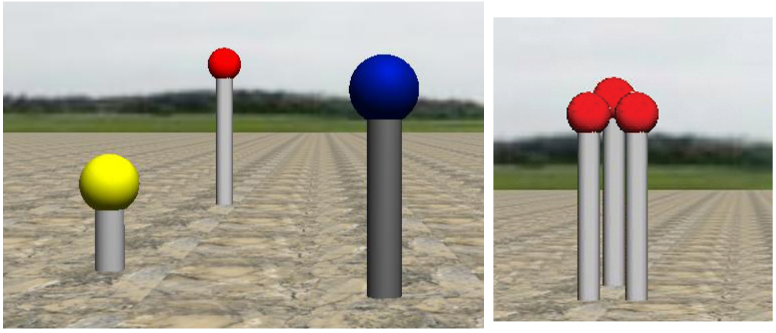
5.5.1 Implementation of Natural 3D Selection Technique

We developed a 3D selection technique to facilitate the use of natural hand gestures. Discussed in section 3.3, we achieved this by placing the GRAB arms within the ReaCToR and repositioning the visual representation of the 3D haptic contact points to the tips of the user's fingers. Shown in Figure 5.3, the user was able to perform selection tasks and experience force feedback in an 1-to-1 manner, corresponding to the ballistic hand movements applied through the haptic arms. Due to the proximity of the 3D haptic contact points to the physical location of the users fingers, we found that this setup reinforced an intuitive method of interaction.

To validate the user experience of the selection technique developed, we conducted a set of usability studies with expert users. Rather than align the 3D haptic contacts points to the exact position of the thimble joints, we found a position of 1cm in front of the hands preferable. We did this to avoid occlusion errors during movement and reduce the technical challenges of maintaining strict co-location between the physical shape of the thimble and haptic contact point. Discussed in section 3.3.2, we were also able to compensate for the range of image distortions associated with stereo multi-screen projections and head tracking instability. Through these tests, we defined a shape and reduced size of the 3D haptic contact point to a small grey sphere of 1 cm in diameter for each arm. With this setup, participants were able to select targets within their arms reach freely similar to touching objects with a pointed finger.

5.5.2 Implementation of IVE Experiment

By using the developed 3D selection technique, we presented an experiment where we instructed participants to perform a series of 3D selection tasks. Based upon a Fitts' law style experiment, the GRAB arms were used to select a series of simply rendered 3D targets. Shown in Figure 5.4, participants were able to move either hand and select 3D objects that exerted haptic feedback only upon selection, and within their arm's reach. During the design phase of the IVE and interaction technique, we had no preconceived ideas of the variables affecting selection performance. Therefore, we made the selection tasks as generic



(a) Example of red, blue and yellow selection targets (b) Example of reset spheres

Figure 5.2: Design of IVE experiment

(a) User in typical operating position

(b) Diagram of virtual representation selection technique

Figure 5.3: Typical operation of hardware and implemented natural 3D selection technique

(a) Example of participant selecting two targets

(b) Example of participant selecting reset spheres

Figure 5.4: Example selection task and reset instructions

as possible, varying only position of the 3D targets and perceived stiffness upon selection. We used the same experimental design to evaluate both right handed and two handed interaction types.

The experiment consisted of three target objects: one blue, one red and one yellow coloured sphere targets placed on grey rods within an environment. When presented, the experimentor issued instructions to select either the blue, red or yellow target in a pre-defined order. Upon task completion, a set of reset spheres would appear to then select, upon which a new arrangement of sphere targets would be loaded in front of the participant to then select. By doing so, we ensured that each participant always performed every selection tasks from the same position.

Shown in Figure 5.3(b), we placed these targets within an outdoors scene. This gave a fixed horizon level which helped reduce any adverse side effects caused by simulator sickness. We also used colours that had a high contrast as not to confuse the participants. By using the values from section 3.2.2, this defined a usable work space which all targets were placed.

To evaluate the influence of haptic force feedback when performing these tasks, we tested three different force feedback conditions. These were only activated upon selection and we offered no visual deformation feedback for each of these interactions:

1. *No Haptic Force Feedback ('NoF conditions')*- No force feedback cues when in contact/selecting a target.

2. *Hard Haptic Force Feedback ('Hard conditions')*- A hard force feedback response when a target is selected, similar to touching a wooden or marble table.

3. *Soft Haptic Force Feedback ('Soft conditions')*- A soft force feedback response when in collision with a target, similar to pressing on a cushion or sponge.

We asked every participant to perform a series of selection tasks that included arrangements of the 3 target objects covering 3 difficulty classes:

1. *Selection of one target ('Select1')*- Only one object in the scene, one blue sphere. Participants were asked to select the blue sphere.

2. *Selection of two targets ('Select2 / Select2,All')*- Only two objects in the scene, one blue and one red sphere. Participants were asked to select the blue sphere and then the red sphere.

3. *Selection of three targets ('Select3 / Select3,All')*- Three objects in the scene, one blue, one red and one yellow sphere. Participants were asked to select the blue sphere, then the red sphere and finally the yellow sphere.

For each of the above selection classes, we identified 15 pre-defined random sphere positions distributed uniformly within the identified workspace. We displayed each of these individual selection tasks from each class all together in a random order. In total, this meant that each participant performed 45 tasks in one go. To further avoid any outside effects on interaction performance, we limited all other variables [WPS+02], and set the size of the spheres to 10cm for all targets. Additionally, depending

	Number of selection trials for task class								
Hands Used:	NoF haptic condition			Soft haptic condition			Hard haptic condition		
	Select1	Select2	Select3	Select1	Select2	Select3	Select1	Select2	Select3
Right	15	15	15	15	15	15	15	15	15
Two handed	15	15	15	15	15	15	15	15	15

Table 5.1: Number of selection tasks of each participant between haptic conditions and hand interaction types

on the haptic condition tested, all targets had the same physical properties, representative to their visual description and the instructions given.

By using this experimental design, we tested two types of hand interactions: performing selection tasks with both hands and with only the right hand. Table 5.1 gives an overview of the conditions we assessed for each of the hand interaction types tested. Each participant only used one force feedback condition, but did this with both two handed and right handed interaction types- performing 45 selection trials with only their right hand first, and then did another 45 trials using two hands or vice versa. There was a 15 minute break between these two sets of 45 trials. To reduce any learning factors, we randomly ordered the interaction type and the list of selection tasks covering the three difficulty sets. Therefore, each participant performed 90 selection tasks.

In the two handed tasks the participants could use either hand to select the next target. In the right handed tasks, they needed to select all targets with one hand. When selected, the target would turn grey- a common visual selection cue. Once all the one, two or three targets were selected in the correct order, two sets of reset markers would appear for both hands to touch in the centre and reposition their hands to where they started as shown in Figure 5.4. At this point, we would automatically load a new selection task to perform. This process repeated until participants completed all tasks covering all three selection task classes.

Based upon experiences in chapter 4, we took a simple approach to the design of the IVE experiment. By doing so, we evaluated colours, sizes and positions for their suitability using expert users. In particular, we placed a lot of attention on limiting the problem of carryover effects. As the experiment consisted of a lot of repetitive tasks, we were aware the participants may become tired leading to a detrimental effect on performance. Therefore, to balance these potential interactions, we randomised the presentation of the selection tasks and order of interaction type. Furthermore, we only evaluated one force feedback condition per participant. This helped to reduce the experiment time to less than 50 minutes limiting the effect of fatigue on selection performance. As a result we used a within subject design separated by haptic feedback condition.

5.5.3 Experiment Procedure and Participants

In total we evaluated 45 participants (33 male and 12 female). From the questionnaires completed, all participants were of similar age (20-25) and backgrounds. All were right handed, physically active, and all had a good appreciation of 3D games (defined as 10 hours or above playing video games per week).

In terms of the demographic of the participants, they were taken from members of the Department of Computer Science at University College London and post-graduate students. 18 participants had previously used the ReaCToR and the GRAB arms. As the experiment was designed to be a set of repetitive tasks, prior knowledge of the equipment did not unduly affect the results given the large sample size. A breakdown of the participant details is given in Table 3 (see Appendix B).

Before starting the experiment, each participant was given an explanation of the study and the departmental ethics approval for this work. We gave each participant a demonstration of the equipment and thorough instructions which lasted 5 minutes. Also, each participant had 10-15 minutes to accustom themselves with the GRAB haptic interface, ReaCToR, head tracking and the implemented 3D interaction technique to level out any learning effects. Once done, we repeated the instructions, answered any questions, and asked if they were ready to continue with the experiment. We logged measurements during the experiment using a system linked to the update loop of the simulation, and when finished we asked each participant to complete a usability questionnaire similar to the one used for chapter 4 [BGH02] (see Appendix A and B).

In total, 15 participants completed each of the three haptic force feedback conditions. Recall that each subject did 45 right handed selection trials first and then 45 two handed selection trials with a 15 minute break in between. The results are thus presented in as a between subjects comparisons of the force feedback methods, whereby each participant performs every type of selection task (Select1, Select2, Select3). We did this to limit any learning effects that may result if participants performed each haptic condition altogether.

To clarify, as the experiment was designed to be a series of repetitive tasks thinking time was not independently evaluated. Also, at the start of each trial we included 15 selection tasks that we discounted in the results, as to eliminate the learning effects on the data of the participants at the start the experiment. When participants made false movements, defined as selecting targets in the wrong order, this was logged by the implemented data capture system and excluded from the results. All other movements were included in the study.

5.6 Results- Right Hand Interaction (R-HI)

To discuss the results, we have used three separate sections: Select1, Select2 and Select3. For a full list of trajectory and velocity graphs (see Apprendix B and attached CD under directory label ‘Appendix B’).

5.6.1 Selection of One Target (Select1)

5.6.1.1 Movement Time (MT)

We found that participants took the least MT to task completion when selecting objects that provided soft force feedback. Shown in Figure 5.5, the average MT to task completion under hard and soft conditions for the majority of tasks was smaller compared to selection without haptic feedback. Summarised in Table 5.2, this difference in MT under hard and soft feedback conditions was 0.038 seconds and 0.106 seconds faster respectively. With respect to the standard deviation results, the difference in MT for soft and NoF conditions was greater than 2. For comparisons between hard and soft conditions, the standard deviation was greater than 1. In contrast, the standard deviation between hard and NoF feedback conditions was less than 1. Therefore, these results suggest that haptic feedback affected MT when selecting a single target. In particular, selecting targets that provided a soft feedback upon contact lead to quicker MT results to task completion.

For a better understanding of this trend, we performed a single factor ANOVA comparing the MT results for each haptic conditioned assessed. To evaluate the significance of the differences observed, we presented this information by collating the number of tasks where the resultant p value was less than 0.05. Shown in Table 5.2, for Select1, we found no significant differences in MT between tasks performed using hard and no force-feedback conditions. In contrast, when selecting targets that exerted soft feedback cues compared to NoF conditions, the results showed that for 9 tasks out of 15 whereby participants performed significantly better. With respect to differences between hard and soft feedback conditions, we found only 5 tasks where participants achieved quicker MT results when selecting soft targets. These findings confirm that selecting targets under soft feedback conditions led to smaller MT results to task completion. Other interesting results include that hard responses was detrimental to MT performance, producing similar results to poorly performing no feedback conditions.

5.6.1.2 Distance Travelled (DT)

Participants took the shortest path to task completion under soft feedback conditions. Shown in Figure 5.6, the average DT to task completion was smallest when selecting targets with soft feedback but largest under NoF conditions. From Table 5.2, the DT under soft feedback conditions compared to selection with haptic and no responses was smaller by 0.013m and 0.029m respectively. For differences between hard and soft feedback conditions, participants took on average 0.013m longer when selecting targets with hard responses. At most, the difference between soft and no feedback was just over 1 standard deviation, whilst comparisons between hard and no feedback conditions were less. Therefore, these results suggest that the least DT to task completion was achieved under soft haptic conditions.

From the ANOVA results, the difference in DT was significant for comparisons between soft and NoF conditions. Shown in Table 5.2, the difference in DT between soft haptic conditions compared to selection with hard and no responses led to p values less than 0.05 in 2 and 7 tasks respectively. With respect to the differences between hard and soft conditions, we found 3 tasks where participants took a significantly longer path when selecting targets with hard feedback. This result suggests that DT performance was best when selecting single targets that exert soft feedback responses. Interestingly, the difference in DT between hard and NoF conditions was small.

5.6.1.3 Velocity Taken (VT)

Unlike results for MT and DT, participants selected the single target using similar average velocities for all the three haptic conditions. Shown in Table 5.2, whilst the average VT to task completion was highest under NoF conditions, compared to selection with hard and soft haptic feedback the difference was only 0.004m/s and 0.002 m/s respectively. These differences in VT between all haptic conditions were all within 1 standard deviation. This indicated a small benefit in VT performance when selecting targets

Table 5.2: Right Handed Interaction (R-HI), Selection of one target (Select1), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

Average Performance

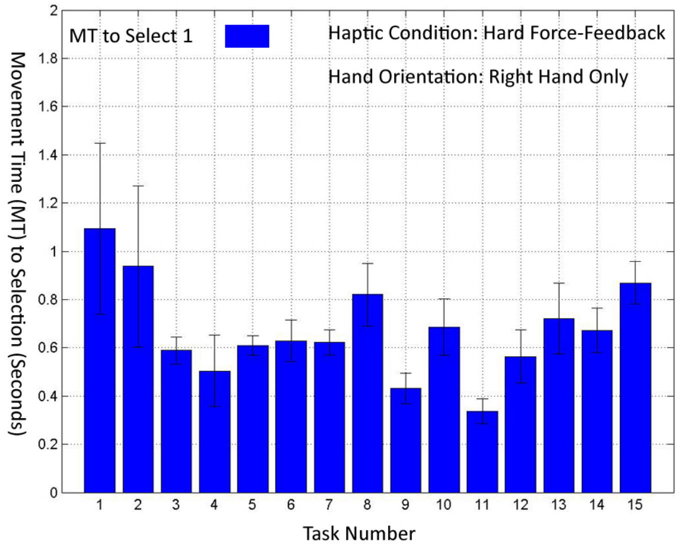
Haptic Condition:	MT	DT	VT
Hard	0.672	0.181	0.280
Soft	0.605	0.168	0.282
NoF	0.711	0.198	0.284

Standard Deviation

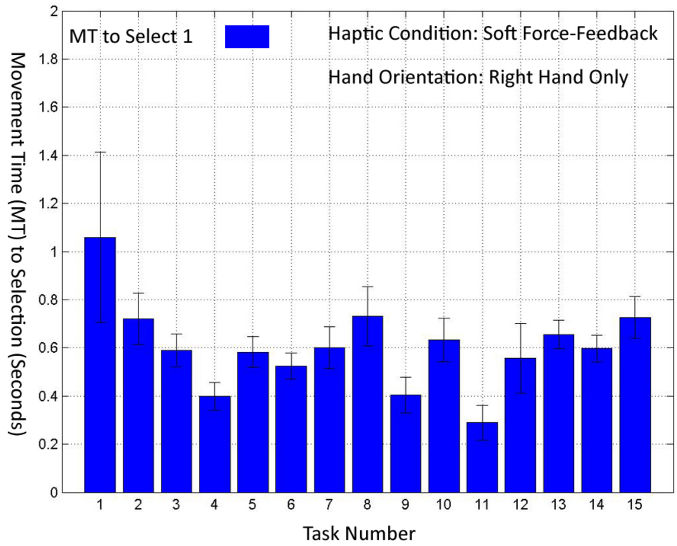
Haptic Condition:	MT	DT	VT
Hard	0.196	0.077	0.090
Soft	0.178	0.073	0.095
NoF	0.206	0.082	0.089

Number of tasks whereby difference between haptic conditions achieved p values < 0.05

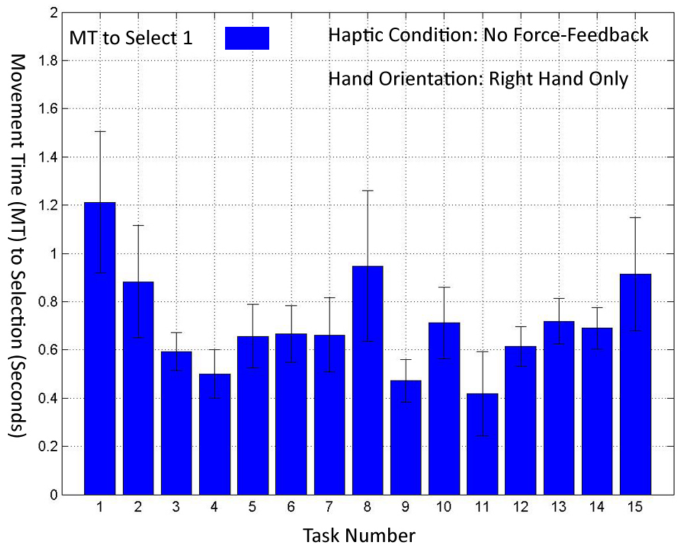
Haptic Condition:	MT	DT	VT
Hard vs NoF	0	2	0
Hard vs Soft	5	3	2
Soft vs NoF	9	7	2



(a) Hard haptic conditions

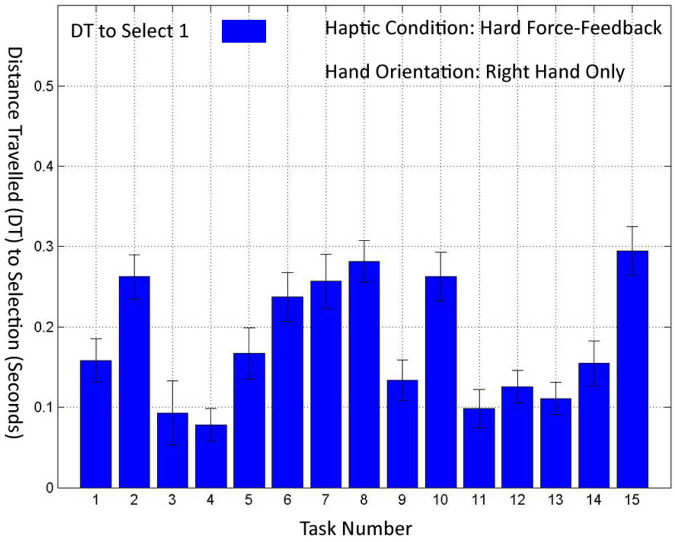


(b) Soft haptic conditions

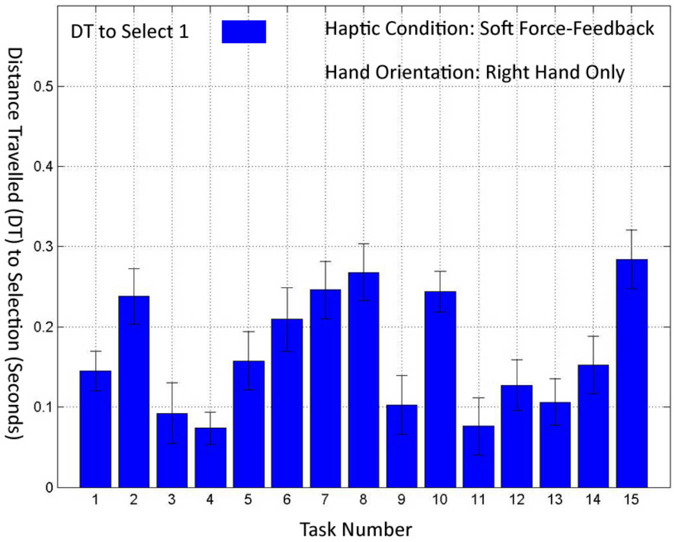


(c) NoF haptic conditions

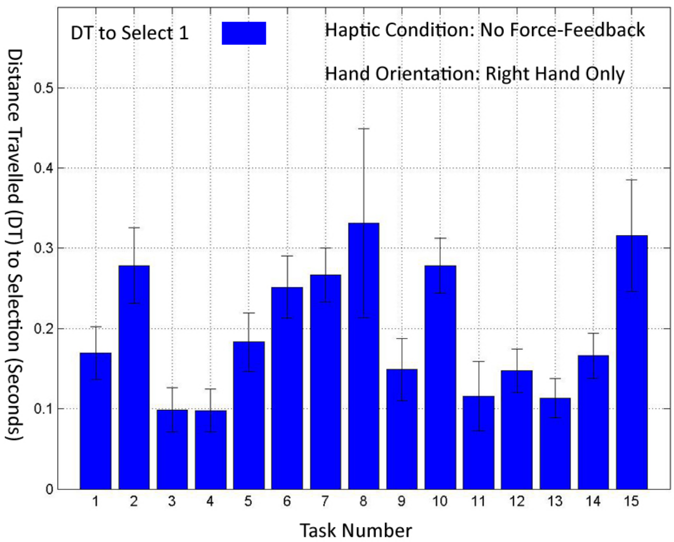
Figure 5.5: Right handed interaction (R-HI), Selection of one target (Select1), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

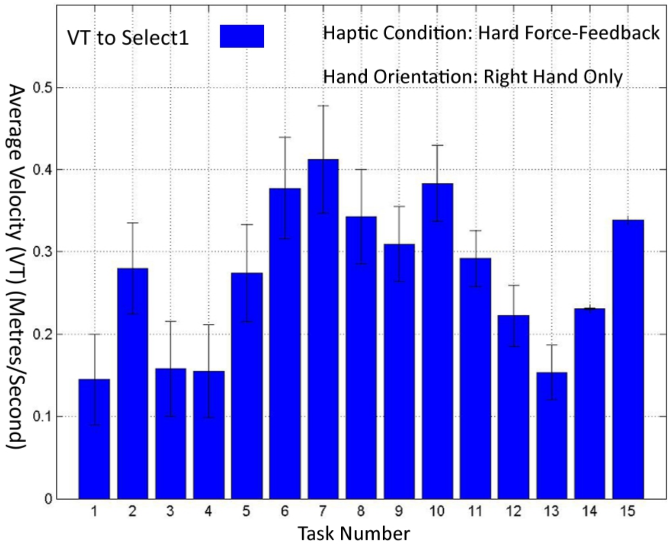


(b) Soft haptic conditions

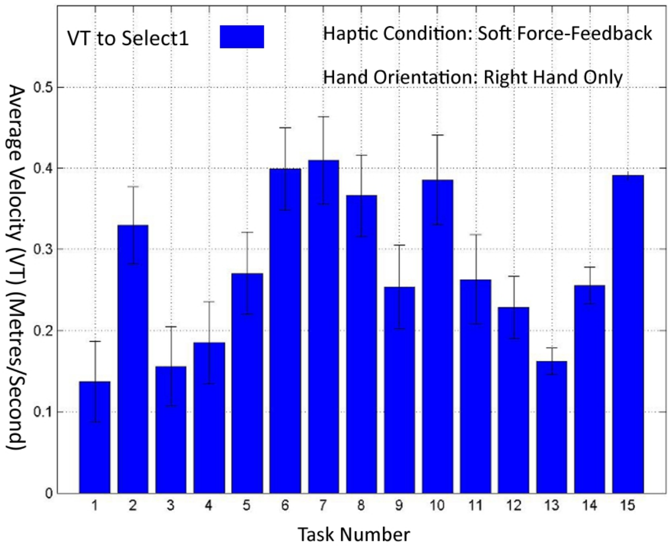


(c) NoF haptic conditions

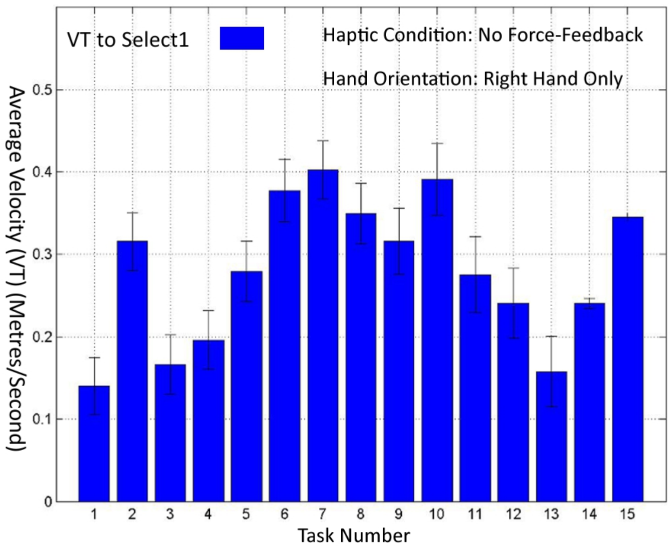
Figure 5.6: Right handed interaction (R-HI), Selection of one target (Select1), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

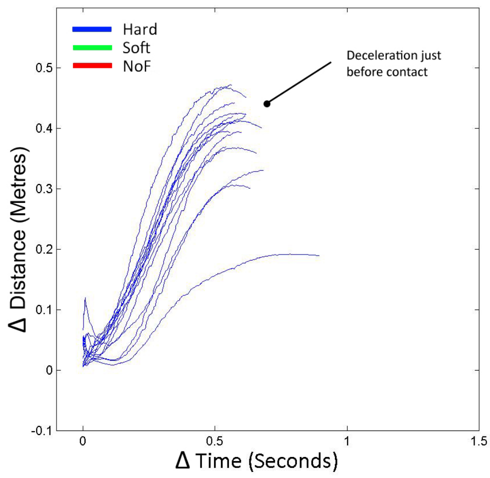


(b) Soft haptic conditions

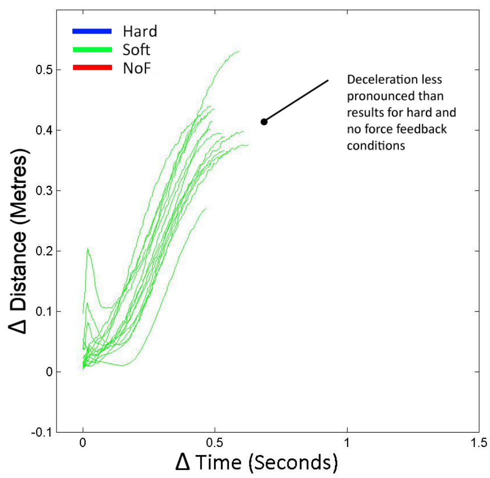


(c) NoF haptic conditions

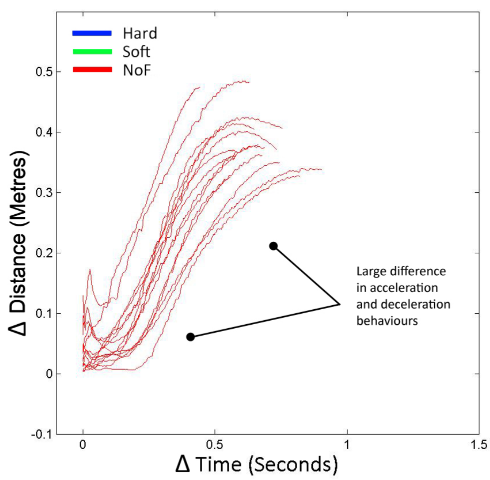
Figure 5.7: Right handed interaction (R-HI), Selection of one target (Select1), Average VT under hard, soft and NoF haptic conditions



(a) Hard haptic condition

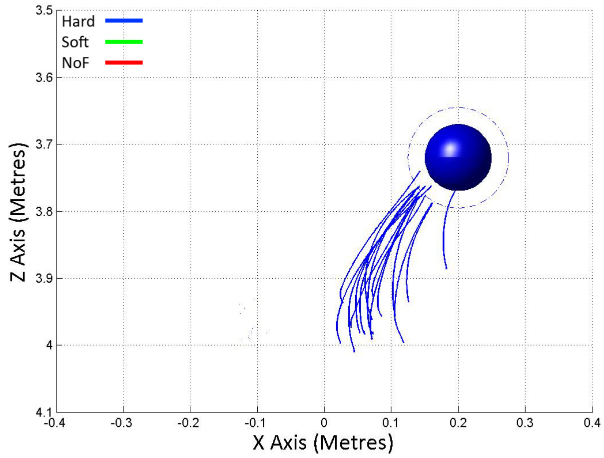


(b) Soft haptic condition

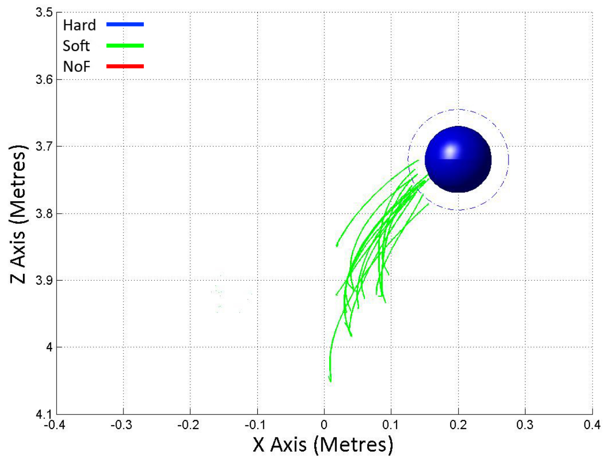


(c) NoF haptic condition

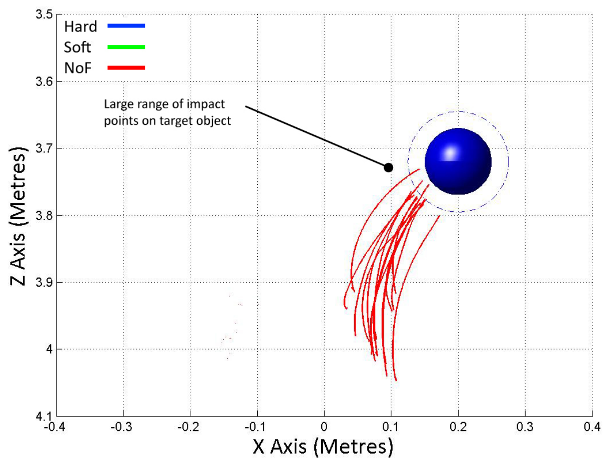
Figure 5.8: Right handed interaction (R-HI), Selection of one target (Select1), VT profile for task 6 under hard, soft and NoF haptic conditions



(a) Hard haptic condition

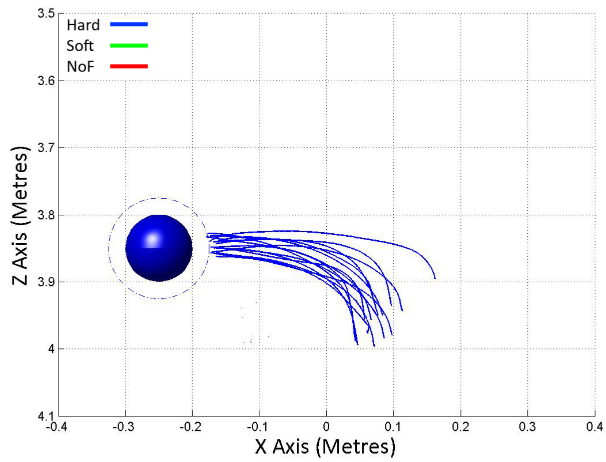


(b) Soft haptic condition

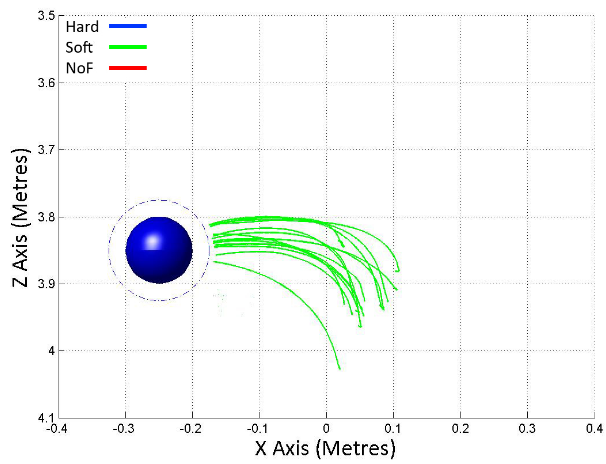


(c) NoF haptic condition

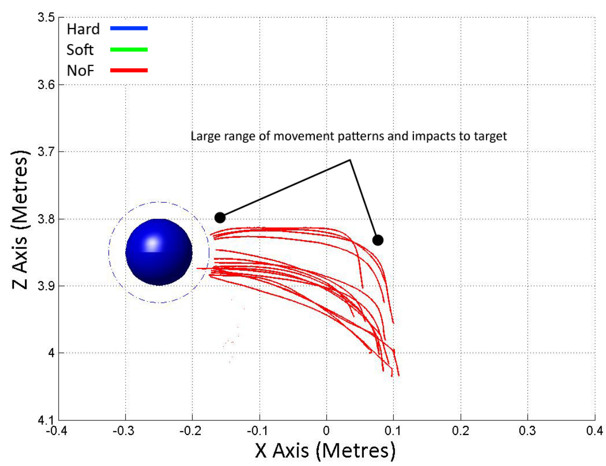
Figure 5.9: Right handed interaction (R-HI), Selection of one target (Select1), Trajectory ZX profile for task 5 under hard, soft and NoF haptic conditions



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 5.10: Right handed interaction (R-HI), Selection of one target (Select1), Trajectory ZX profile for task 13 under hard, soft and NoF haptic conditions

without haptic feedback.

From the ANOVA results, the differences in VT between haptic feedback conditions were not significant. From Table 5.2, we found only 2 tasks where the differences in VT between haptic feedback conditions led to p values less than 0.05. Therefore, this suggests there was no difference in the average VT when selecting a single target.

To understand the change in velocity throughout each task, we plotted the velocity profiles of every participant for each task. Shown in Figure 5.8, the acceleration profiles when moving to select a single target was similar for each haptic condition. For Task 6, participants reached a peak velocity near 0.5m/s just before selection of the target. This behaviour was similar for each haptic condition and other selection tasks assessed. For a full list of velocity profiles see Appendix B.

5.6.1.4 Trajectory Analysis

To understand the ballistic movements made, we plotted the trajectories participants took for each selection task. Based upon results reported for MT and DT, we found that when moving to the single target, the hand trajectories used for all three haptic force feedback conditions assessed were very similar. As shown in Figures 5.9 and 5.10, the participants took similar arching movements to select the face of the target directed in line with the viewing perspective. Nevertheless, there were small noticeable differences between haptic conditions.

When selecting targets under hard and soft force feedback conditions, we found that the spread of impact points made were smaller in comparison to the behaviour observed under NoF conditions. From Appendix B, the trajectory maps show differences in the impact points made between soft and hard feedback conditions, to those for no feedback conditions. In particular, when comparing the impact points under hard haptic conditions compared to selection with no feedback, this resulted in the biggest difference in impact points. However, with respect to changes in MT and DT, the effect of these different impact points were small.

5.6.2 Selection of Two Targets (Select2)

5.6.2.1 Movement Time (MT)

When selecting two targets, we found that selection under soft feedback conditions achieved the quickest MT results to task completion. Shown in Figure 5.11, this was evident for the majority of selection tasks. From Table 5.3, the average MT under hard and NoF conditions compared to selection with soft force feedback was slower by 0.131 seconds and 0.097 seconds to task completion respectively. Differences in MT between both hard and soft conditions, and soft and NoF conditions were greater than 1 standard deviation. For comparisons between hard and NoF conditions, the difference in MT was less than 1 standard deviation. As a result, this indicates that when selecting two targets soft feedback conditions lead to quicker MT to task completion. Interestingly, these findings also suggests that hard haptic responses were detrimental to MT performance.

With respect to the sub-tasks, for movements to both the first and second targets the quickest MT was achieved under soft force feedback conditions. From Table 5.3, MT for Select2,1 when selecting targets that provide soft feedback compared to hard and NoF haptic conditions was smaller by 0.077 seconds and 0.068 seconds respectively. For Select2,2, the difference in MT between the three haptic conditions was: (Hard-Soft), 0.054 seconds; and (NoF-Soft), 0.029 seconds. In contrast, MT under hard conditions compared to selection without haptic feedback for Select2,1 and Select2,2 was slower by 0.009 seconds and 0.026 seconds respectively. With respect to the standard deviation results, comparisons between hard and soft conditions, and soft and no feedback conditions were greater than 1. Conversely, differences between hard and no feedbacks were less than 1 standard deviation. These results suggest that besides average MT to task complete, soft feedback conditions improved the time taken to select the first and second target.

From the ANOVA results, the difference in MT to task completion and Select2,1 when selecting targets with soft feedback was significant. Summarised in Table 5.3, we found 7 and 6 tasks for Select2,All whereby the difference in MT under soft haptic conditions compared to selection with hard and no feedback achieved p values less than 0.05. The same result was also found for Select2,1. However, when moving to the second target the difference in MT between feedback conditions led to p values greater than 0.05 for the majority of selection tasks. Therefore, this indicates that soft feedback conditions improves MT performance when moving to the first target.

5.6.2.2 Distance Travelled (DT)

Participants took a longer DT to select two targets with no force feedback. Shown in Figure 5.6, the least DT to task completion was achieved when selecting targets that exerted hard force feedback, closely followed by results under soft haptic conditions. From Table 5.3, the average difference in DT under hard and soft responses compared to selection with no force feedback was smaller by 0.181m and 0.177m respectively. These differences between hard and soft feedback against selecting targets with no response were greater than two standard deviations. In contrast, the difference in DT between hard and soft feedback conditions were less than 1 standard deviation. Therefore, this suggests the shortest paths taken to task completion was achieved when selecting targets with hard and soft force feedback.

When comparing DT results between the sub-tasks, the longest path was taken when moving to select the first target. Shown in Figure 5.6, we found that for most tasks the DT taken to the first target is much greater than the subsequent path taken to the second target. From Table 5.3, the average DT for the 3 haptic conditions were: Hard, Select2,1- 0.191m, Select2,2- 0.072m; Soft, Select2,1- 0.177m, Select2,2- 0.090m; and NoF, Select2,1- 0.209m, Select2,2- 0.235m. Interestingly, when selecting targets under hard and soft feedback conditions there was decrease in DT when moving from Select2,1 to Select2,2. In contrast, under NoF conditions participants took a longer path to select the second target. This indicated that when selecting targets with haptic feedback, there is a benefit to DT performance when moving to the second target.

We assessed the significance of the observed trends in DT by performing a set of ANOVA comparisons between each condition. From Table 5.3, we found that in 15 tasks when selecting hard targets, and in 14 tasks when selecting soft targets compared to selection with NoF conditions, the difference in DT led to p values less 0.05. With respect to results for hard haptic conditions against selection with soft feedback to task completion, we found only 1 task where the difference in DT was significant. This trend between feedback condition was also similar to that recorded for Select2,2. Conversely, when moving to select the first target the number tasks indicating a significant difference in DT results between feedback conditions was reduced. As a result, these results suggest that DT performances to task completion and Select2,2 were best under hard and soft feedback conditions.

5.6.2.3 Velocity (VT)

For Select2, participants performed with the greatest velocity under NoF conditions. Shown in Table 5.3, the average VT to task completion for NoF conditions compared to selection under hard and soft feedback conditions was slower by 0.154m/s and 0.128m/s respectively. VT under soft feedback conditions was faster by 0.024m/s. With respect to the standard deviation results, the difference in VT between hard and soft haptic conditions to selection without force feedback was greater than 2. In contrast, the difference in VT between hard and soft feedback conditions was small and within 1 standard deviation. This demonstrates that VT performance was best selecting targets without haptic feedback.

For the sub-tasks, VT was quickest for both Select2,1 and Select2,2 under NoF conditions. From figure 5.7, we found that whilst VT drops upon selection of the first target for both haptic feedback conditions, VT increases for the same phase when selecting targets that exert no force feedback. This is an interesting result suggesting that under NoF conditions participants were able to maintain their overall velocity better when moving between targets.

From the ANOVA results, we found the biggest difference in VT between feedback conditions at Select2,2. From Table 5.3, for Select2,1 at most there was only 3 tasks indicating a significant difference in VT between all three feedback combinations. In contrast, for Select2,2 differences in VT under NoF conditions compared to selection with hard and soft feedback this led to 15 tasks with p values less than 0.05. This was also true for comparisons between soft and hard feedback conditions with 11 tasks. As a result, this shows that VT over two targets was quickest under NoF conditions. In particular, these findings suggest that the biggest difference in VT between all three feedback conditions occurred when moving to select the second target.

To understand this VT behaviour in more detail, we plotted the profiles for all participants and tasks. Shown in Figure 5.14, whilst the peak velocities for all three feedback conditions are similar to the first target, participants are able to accelerate to a higher peak velocity better when moving to the second target when using targets that exert no force feedback. Interestingly, these profiles also show common to all conditions, participants upon selection pause before moving on. Again, from these results, this showed that both haptic feedback conditions were detrimental to VT performance as the acceleration to the second target was slower.

5.6.2.4 Trajectory Analysis

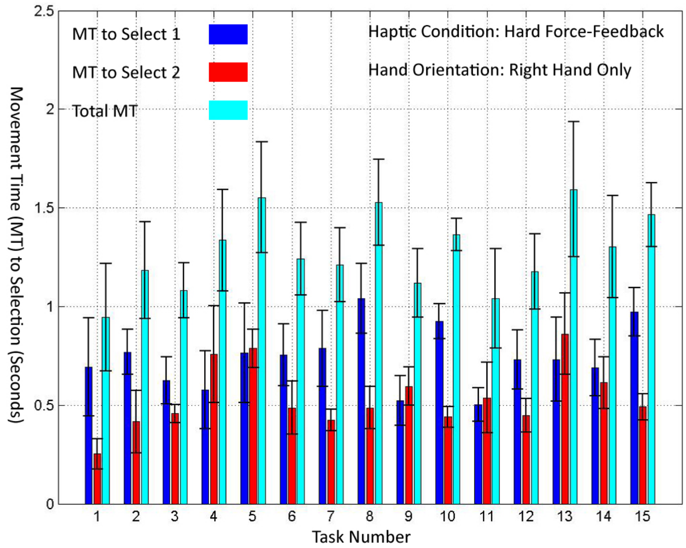
For a better understanding of the MT and DT results, we plotted the trajectory maps for the 15 tasks covering the selection of two targets. In Figures 5.15 and 5.16, we begin to see variations in the trajectory and spread of impact points on the first target, moving onto the second. In particular, as shown in Figure 5.15(c), we can see a greater spread of impact points on the surface of specifically the first target without

Table 5.3: Right Handed Interaction (R-HI), Selection of two targets (Select2), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

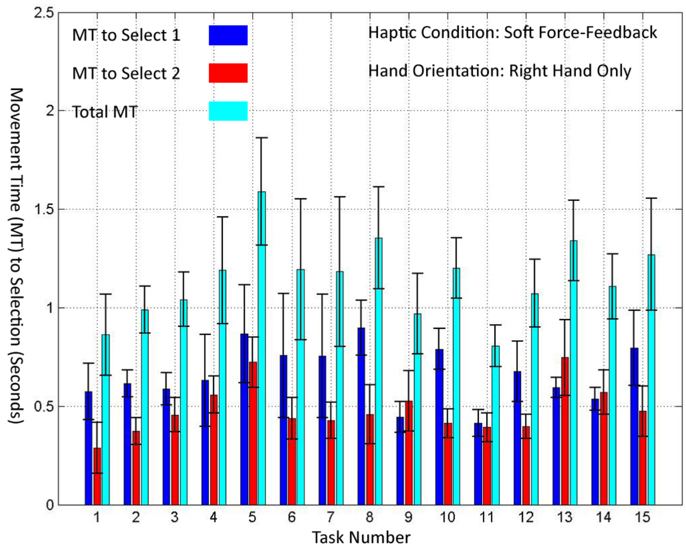
Average Performance			
Haptic condition	MT		
	Select2,1	Select2,2	Select2,All
Hard	0.739	0.537	1.276
Soft	0.662	0.482	1.144
NoF	0.731	0.511	1.241
	DT		
Hard	0.191	0.072	0.263
Soft	0.177	0.091	0.267
NoF	0.209	0.235	0.444
	VT		
Hard	0.261	0.136	0.211
Soft	0.267	0.200	0.238
NoF	0.285	0.455	0.366

Standard Deviation			
Haptic condition:	MT		
	Select2,1	Select2,2	Select2,All
Hard	0.154	0.162	0.196
Soft	0.145	0.125	0.202
NoF	0.171	0.132	0.189
	DT		
Hard	0.021	0.008	0.024
Soft	0.035	0.009	0.039
NoF	0.028	0.072	0.086
	VT		
Hard	0.067	0.067	0.058
Soft	0.076	0.100	0.075
NoF	0.072	0.193	0.113

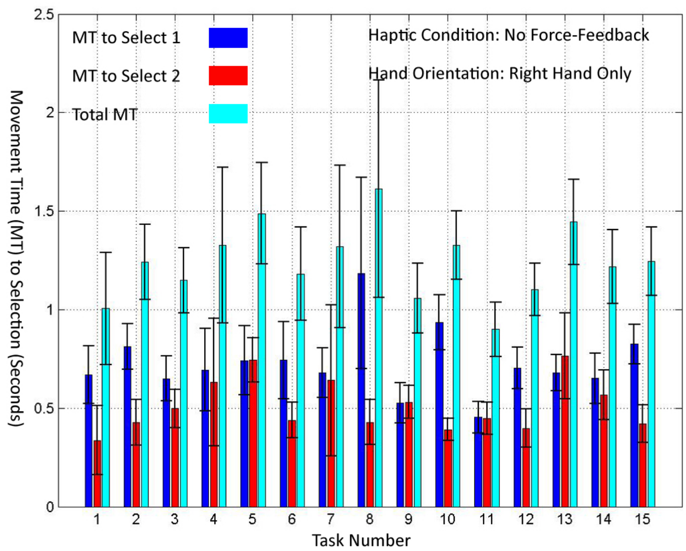
Number of tasks whereby difference between haptic conditions achieved p values < 0.05			
Haptic Condition:	MT		
	Select2,1	Select2,2	Select2,All
Hard vs NoF	1	3	1
Hard vs Soft	7	2	7
Soft vs NoF	6	1	6
	DT		
Hard vs NoF	1	14	15
Hard vs Soft	3	6	1
Soft vs NoF	6	13	14
	VT		
Hard vs NoF	3	15	15
Hard vs Soft	1	11	5
Soft vs NoF	3	15	13



(a) Hard haptic conditions

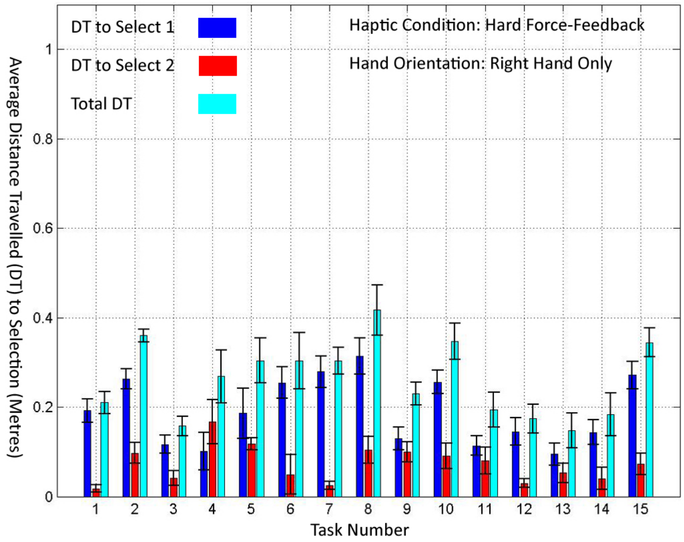


(b) Soft haptic conditions

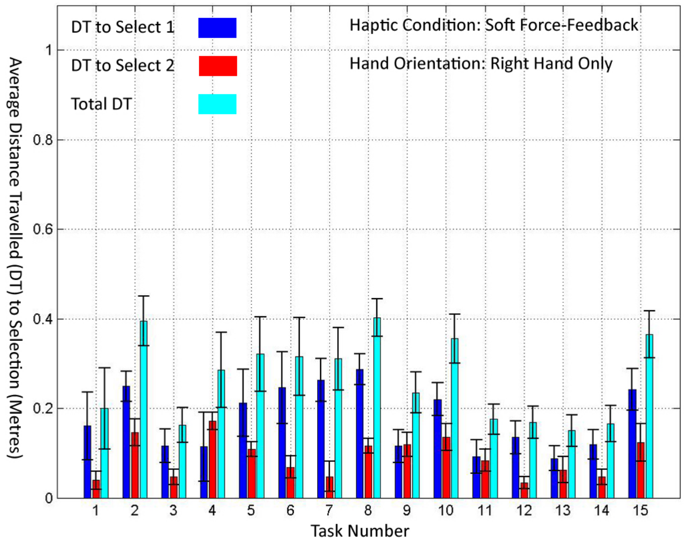


(c) NoF haptic conditions

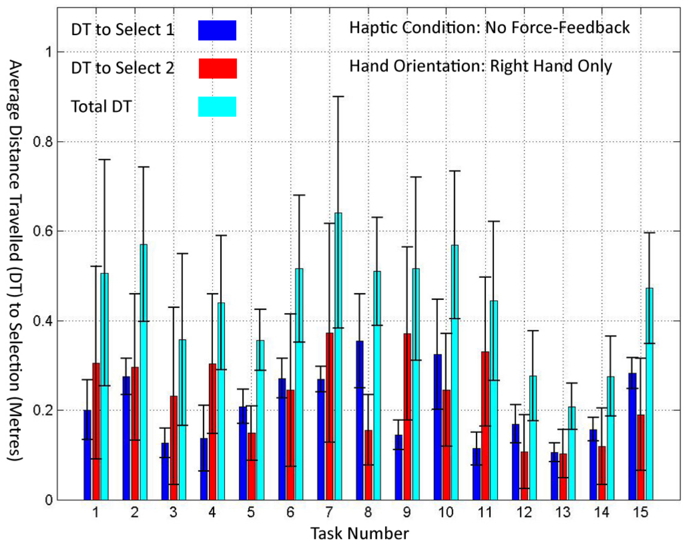
Figure 5.11: Right handed interaction (R-HI), Selection of two targets (Select2), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

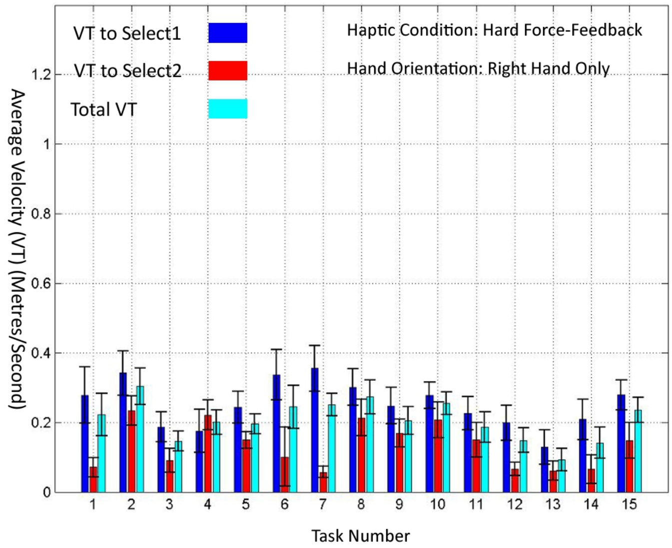


(b) Soft haptic conditions

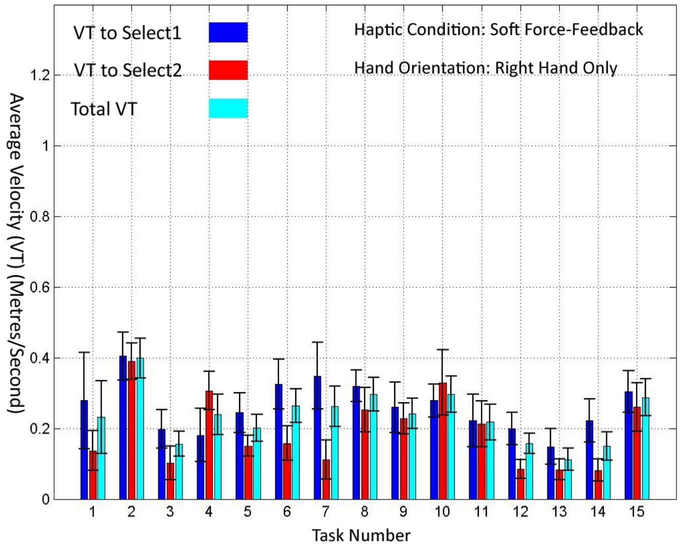


(c) NoF haptic conditions

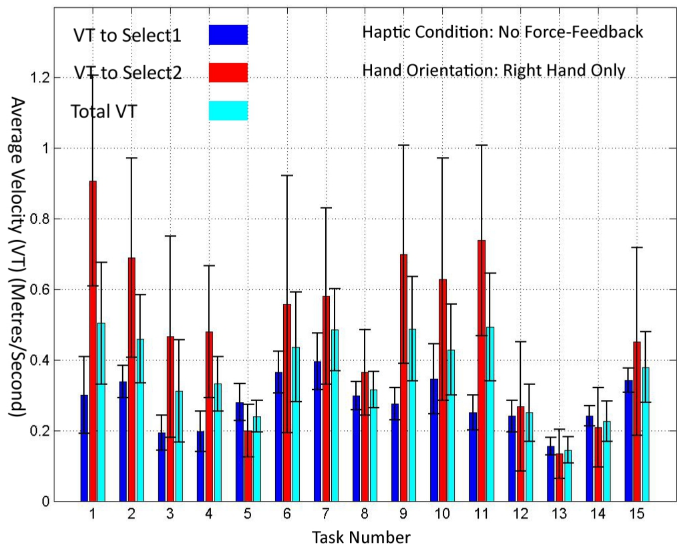
Figure 5.12: Right handed interaction (R-HI), Selection of two targets (Select2), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

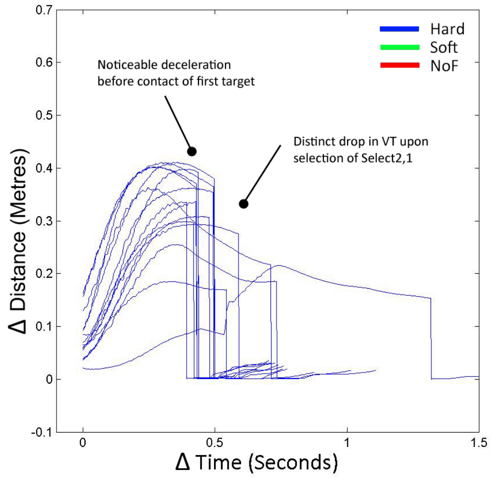


(b) Soft haptic conditions

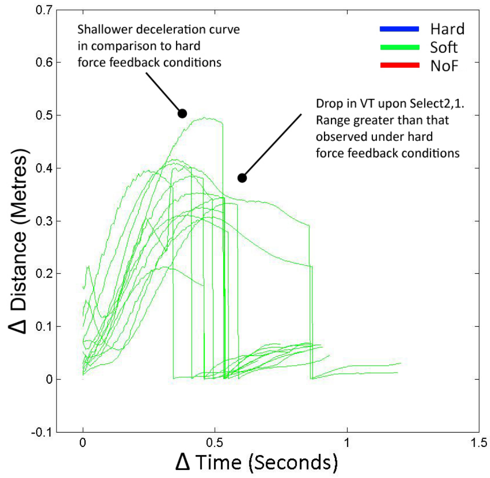


(c) NoF haptic conditions

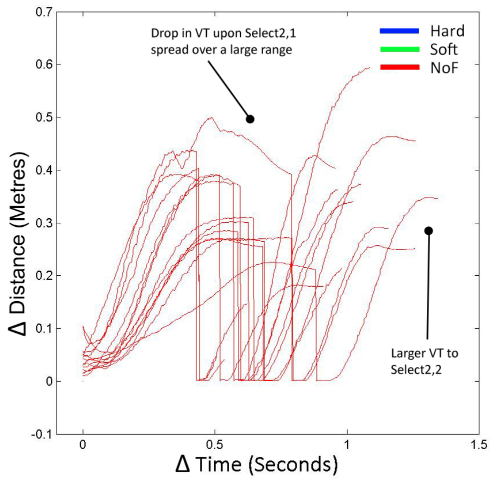
Figure 5.13: Right handed interaction (R-HI), Selection of two targets (Select2), Average VT under hard, soft and NoF haptic conditions



(a) Hard haptic condition

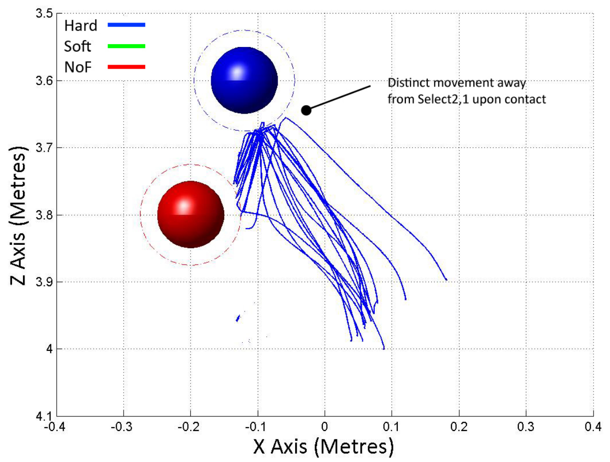


(b) Soft haptic condition

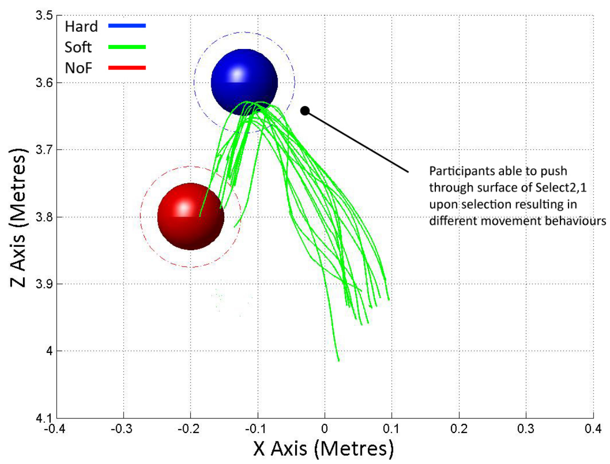


(c) NoF haptic condition

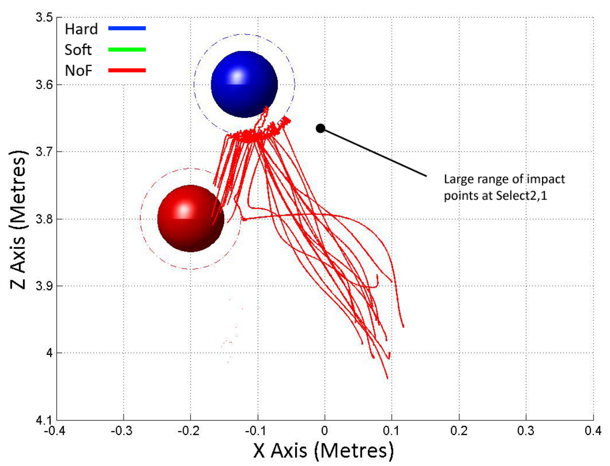
Figure 5.14: Right handed interaction (R-HI), Selection of two targets (Select2), VT profile for task 16 under hard, soft and NoF haptic conditions



(a) Hard haptic condition

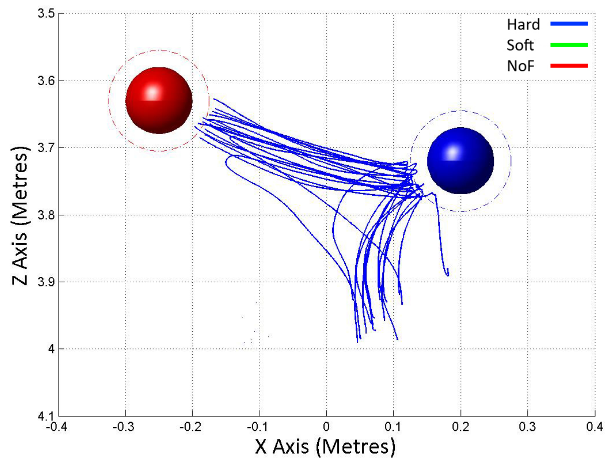


(b) Soft haptic condition

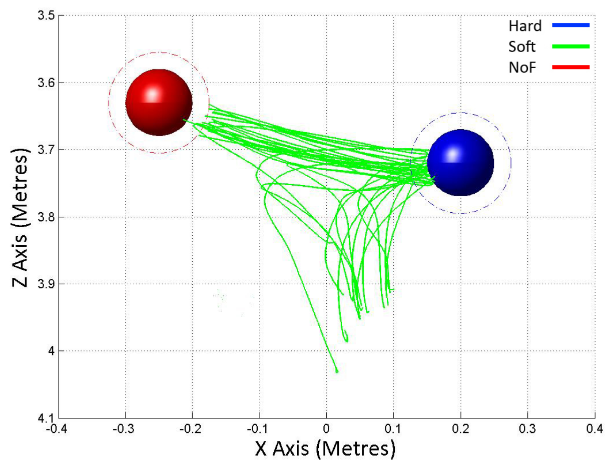


(c) NoF haptic condition

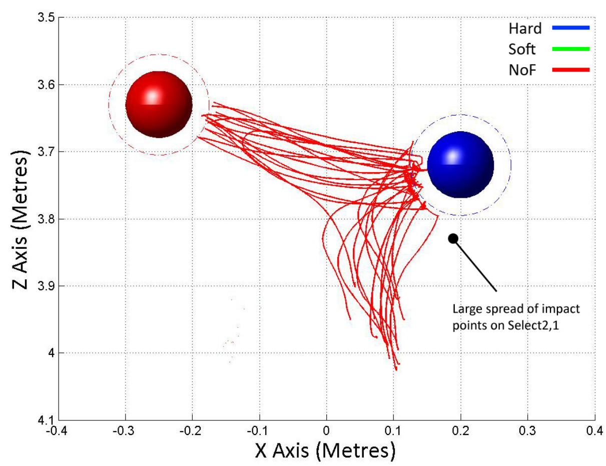
Figure 5.15: Right handed interaction (R-HI), Selection of two targets (Select2), Trajectory ZX profile for task 17 under hard, soft and NoF haptic conditions



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 5.16: Right handed interaction (R-HI), Selection of two targets (Select2), Trajectory ZX profile for task 20 under hard, soft and NoF haptic conditions

haptic feedback in comparison to selecting with soft and hard responses. This resulted in larger DT trajectories as participants selected a point on the first target which required a longer path to the second target.

Interestingly, another key distinction between haptic conditions is behaviour on and within the target. As we can see in Figure 5.15(b) and 5.15(c), participants spend more time on and within the surface of targets that exert no feedback. In comparison, under hard feedback conditions upon selection participants spread very little time on the surface instantly moving away from the target once feedback has been registered. Similarly, under soft feedback results upon selection with soft targets participants spent less time on the surface of the target moving to second more efficiently. Due to this extra cost, this difference in the behaviour on the surface of the target resulted in extra DT and MT taken for conditions with no feedback. However, as these objects did not provide resistance upon contact this explains the larger VT values observed.

5.6.3 Selection of Three Targets (Select3)

5.6.3.1 Movement Time (MT)

When selecting three targets, participants achieved the quickest MT results under soft feedback conditions. From Table 5.4, the average MT under soft haptic conditions compared to selection with hand and NoF feedback was smaller by 0.358 seconds and 0.150 seconds respectively. In contrast, participants took the most time when selecting all three targets under hard feedback conditions, 0.208 seconds slower to selection with NoF feedback. With respect to the standard deviation results, the difference between hard and soft, and hard and NoF conditions were greater than 2. This suggests that the observed MT behaviour was dependent on the type of haptic condition. As with Select2, we found that whilst soft feedback conditions improved performance, hard responses had a negative effect on MT to task completion.

For the sub-tasks, we found that hard feedback responses produced the largest MT for both movements whereas selection under soft feedback conditions achieved the quickest. Shown in Figure 5.17, MT when selecting the second and third targets was similar for each of the haptic conditions, suggesting a levelling in performance. With respect to results for Select3,2 compared to Select3,1, MT for hard, soft and NoF feedback conditions was smaller by 0.234 seconds, 0.202 seconds and 0.301 seconds respectively. This suggests that participants took a longer time in selecting the first target, with the biggest difference observed under NoF conditions. These findings demonstrate the changes in MT between haptic feedback conditions and movements between targets.

From the ANOVA we found that the differences in MT between feedback conditions and sub-tasks were significant. Shown in Table 5.4, for task completion, we observed 11 and 8 tasks where selecting hard targets lead to larger MT results with p values less than 0.05 compared to selecting targets with soft and NoF conditions respectively. With respect to results under soft haptic conditions against selection with no feedback, we found only 3 tasks where the difference in MT was significant. This is an interesting observation, suggesting that the MT behaviour under hard feedback condition is different to selection with targets providing soft and no responses. This trend was also evident for the sub-tasks, whereby the number of tasks recording p values less than 0.05 increased when comparing MT under hard haptic conditions to results when selecting with soft and no feedback. Therefore, these findings suggest that MT between soft and no feedback conditions were similar, whilst selecting targets with hard responses led to larger time taken to complete the task and its sub-tasks.

5.6.3.2 Distance Travelled (DT)

The smallest DT to task completion when selecting three targets occurred under soft force feedback conditions. From Table 5.4, the longest path to task completion was achieved under NoF conditions. In comparison, selection for hard and soft feedback conditions achieved on average smaller DT results by 0.265m and 0.273m respectively. Conversely, the average difference in DT when selecting targets with soft feedback compared to hard haptic conditions was only 0.008m. The difference in DT between both hard and soft haptic conditions to selection with NoF conditions was greater than 2 standard deviations. As the difference between hard and soft feedback conditions was less than 1 standard deviation, this demonstrates that DT to task completion was best when selecting targets with haptic feedback.

With respect to the sub-tasks, similar to Select2, the DT behaviour between feedback conditions was different. Shown in Figure 5.18, under hard and soft haptic conditions, the average DT to Select3,1 was larger than Select3,2 and Select3,3. Conversely, for NoF conditions the largest DT occurred at Select3,2. From Table 5.4 for sub-tasks Select3,1 to Select3,2 this difference in DT between hard and soft feedback conditions was 0.086m and 0.077m. When selecting targets with no feedback, rather than decreasing in DT between sub-tasks, the path taken from Select3,1, to Select3,2 increased in size by 0.011m, to then reduce down when moving to select the final target. This showed that selecting targets with haptic feedback improves DT when moving to the second and final targets.

From the ANOVA results, this showed that the DT behaviour when selecting soft targets was different to selecting targets using both hard and no feedback conditions. From Table 5.4, to task completion we found that in 15 tasks the difference in DT under soft haptic conditions to selection with hard and NoF feedback led to p values less than 0.05. Conversely, with respect to comparisons between hard and no feedback results, we only found 3 tasks for Select3,All where the difference in DT was significant. This suggests, that whilst soft feedback responses can improve DT behaviour to task completion, hard response can also have a negative impact producing results similar to poorly performing no feedback conditions. Again, similar to results for Select2, only after selection of the first target, did we find a large difference in DT between haptic conditions. Therefore, these results indicated that DT performance to task completion and sub-tasks was dependent on haptic feedback condition.

5.6.3.3 Velocity Taken (VT)

Participants completed the task with the greatest velocity with targets that did not provide haptic feedback. Shown in Table 5.4, the average VT to task completion under NoF conditions compared to selection with hard and soft feedback was faster by 0.164m/s and 0.128m/s. For differences between haptic feedback conditions, VT under soft conditions was faster than selection with hard feedback by 0.036m/s. The difference in VT between both haptic conditions to selection without force feedback was greater than 2 standard deviations. As a result, this indicates that selection without haptic feedback leads to faster VT performances to task completion.

By analysing the results for each sub-task, VT was quickest for all movements when selecting targets with no force feedback. Shown in Figure 5.19, VT decreased as participants progressed through the individual sub-tasks when using hard and soft haptic feedback conditions. This was not the case when selecting targets with no force feedback - at Select3,2 VT would increase from select3,1 and then decrease when moving to select the final target. This suggests, similar to Select2, participants are able to retain their speed better when selecting multiple targets with no force feedback.

From the ANOVA results, the difference in VT between all haptic conditions were significant. From Table 5.4, by Select3,2 and Select3,3 the difference in VT for all haptic conditions led to p values less than 0.05 in more than 9 tasks. This showed that VT behaviour for the sub-tasks were dependent on haptic feedback. Interestingly, there was a significant difference between selection with soft and hard feedback conditions.

From plotted the velocity profiles, we found that beyond selection of the first target, the acceleration and peak values achieved for the subsequent tasks were different for each haptic condition. Shown in 5.20, for soft and no feedback conditions, participants were able to accelerate and achieve larger peak velocities compared to results achieved when selecting targets with hard feedback. This suggests that participants were able to retain greater velocity when selecting targets with no and soft feedback responses.

5.6.3.4 Trajectory Analysis

Unlike Select2 and Select1, when selecting 3 targets we can see noticeable differences in the trajectories participants took under the three feedback conditions. Specially, the key difference between the conditions are the behaviours on the surface of the targets. As shown in Figures 5.21, and 5.22, whilst under soft and no feedback conditions extra MT and DT was spent within the target object, this was not the case under hard feedback conditions. Specifically, participants moved their hands to a precise point before moving away and then correcting their initial movement to the subsequent target. In contrast, under soft feedback conditions similar target points were made to those under hard feedback conditions; however rather than moving away from the target participants often pushed inside to move to a exit point that had a more optimal path to the next target. Under no feedback conditions, the extra DT and MT was simply spent registering the selection before moving on.

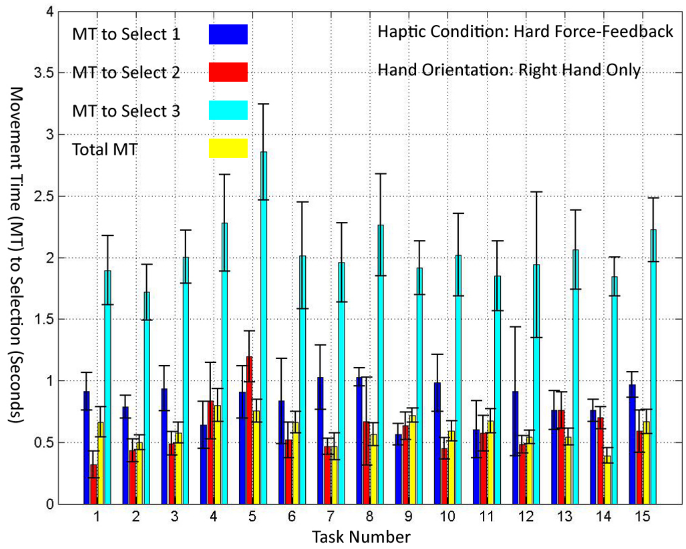
Due to these different behaviours, the impact to performance varied accordingly. Whilst participants under soft feedback conditions were able to benefit from the haptic feedback to choose efficient paths and selection responses, for hard feedback conditions the extra movement away was hindrance to DT and VT between targets. Interestingly, under no feedback conditions the extra effort needed to register selection of the target had an overall detrimental effect on performance.

5.6.4 Qualitative Data Analysis

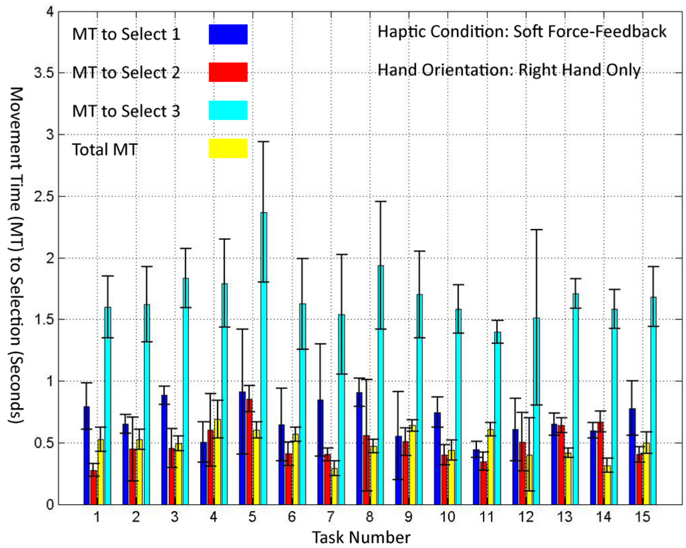
From the qualitative data recorded, we can see the participants found all force feedback conditions easy to use and experienced little sickness. As shown in Figure 5.23, in terms of responsiveness and naturalism of interaction, conditions with haptic force feedback produced best results. The best performing

Table 5.4: Right Handed Interaction (R-HI), Selection of three targets (Select3), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

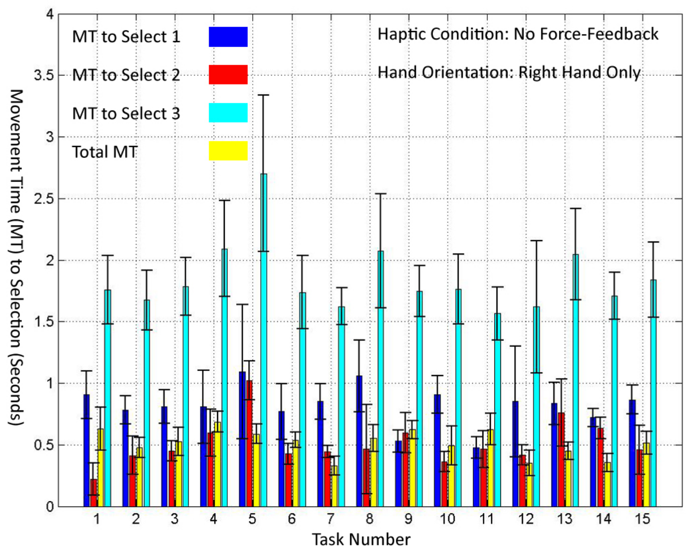
Average Performance				
Haptic condition:	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard	0.842	0.608	0.618	2.067
Soft	0.701	0.499	0.459	1.659
NoF	0.817	0.516	0.521	1.854
	DT			
Hard	0.189	0.103	0.099	0.391
Soft	0.177	0.100	0.107	0.384
NoF	0.224	0.235	0.197	0.656
Haptic condition	VT			
Hard	0.227	0.16	0.162	0.192
Soft	0.256	0.208	0.214	0.228
NoF	0.270	0.48	0.381	0.356
Standard Deviation				
Haptic condition	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard	0.151	0.212	0.112	0.272
Soft	0.149	0.147	0.114	0.228
NoF	0.162	0.189	0.109	0.287
	DT			
Hard	0.083	0.086	0.046	0.038
Soft	0.072	0.055	0.049	0.041
NoF	0.084	0.096	0.059	0.118
	VT			
Hard	0.079	0.084	0.067	0.045
Soft	0.082	0.098	0.085	0.058
NoF	0.081	0.175	0.100	0.059
Number of tasks whereby difference between haptic conditions achieved p values < 0.05				
Haptic condition:	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard vs NoF	9	8	13	11
Hard vs Soft	3	6	9	8
Soft vs NoF	5	3	1	3
	DT			
Hard vs NoF	5	7	7	3
Hard vs Soft	3	12	12	15
Soft vs NoF	8	13	13	15
	VT			
Hard vs NoF	2	10	9	10
Hard vs Soft	7	15	15	15
Soft vs NoF	2	11	12	14



(a) Hard haptic conditions

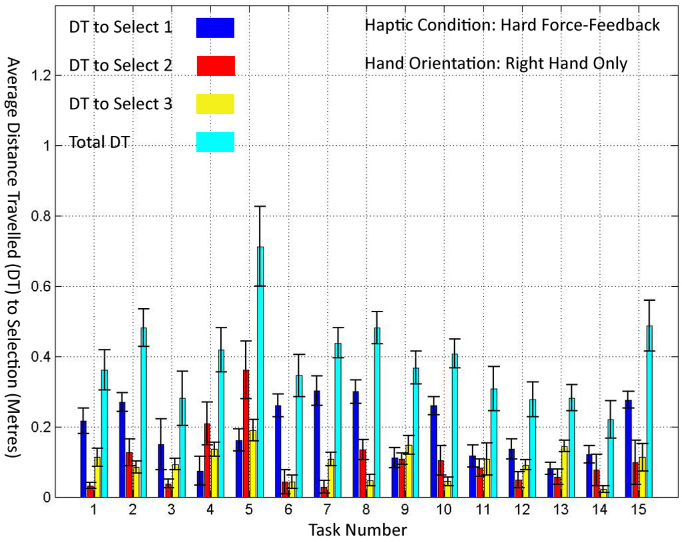


(b) Soft haptic conditions

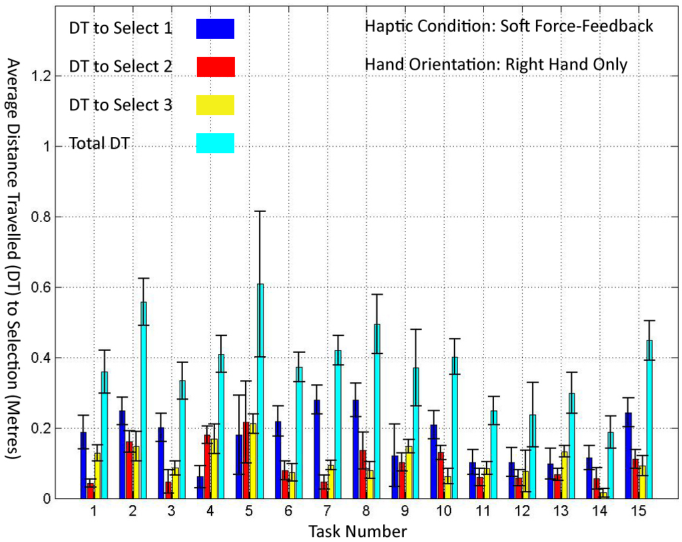


(c) NoF haptic conditions

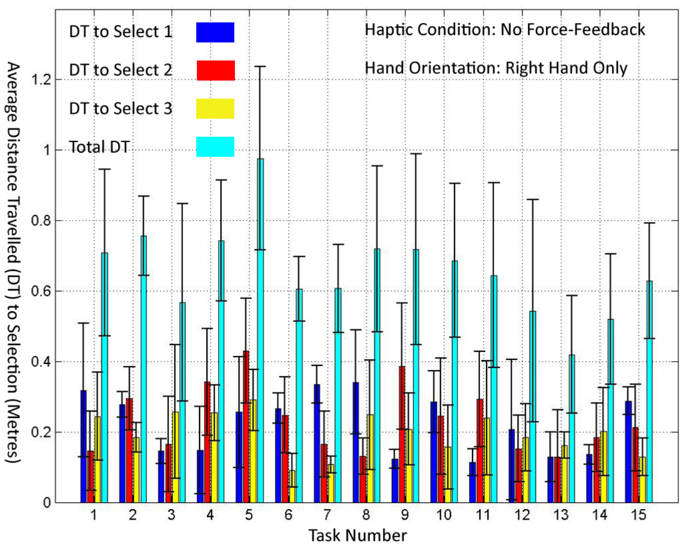
Figure 5.17: Right handed interaction (R-HI), Selection of three targets (Select3), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

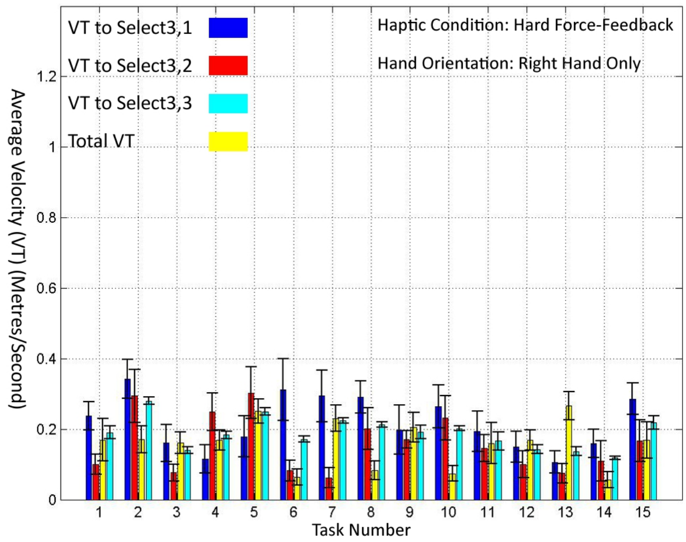


(b) Soft haptic conditions

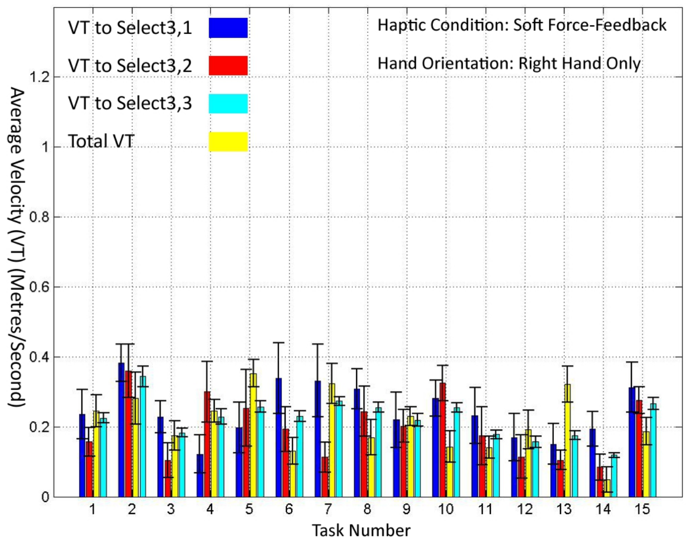


(c) NoF haptic conditions

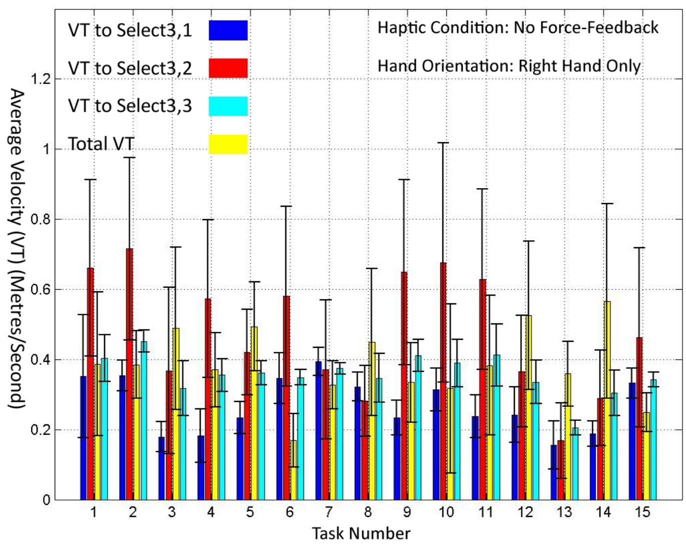
Figure 5.18: Right handed interaction (R-HI), Selection of three targets (Select3), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

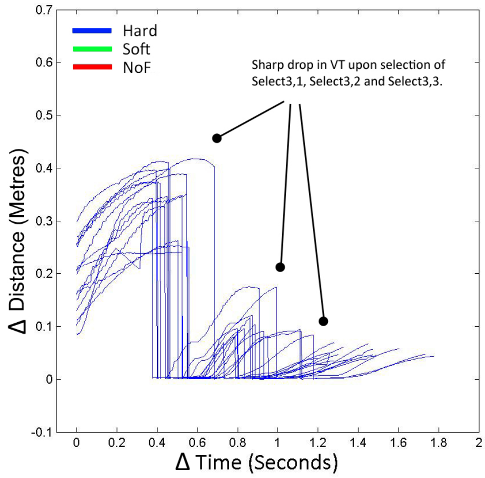


(b) Soft haptic conditions

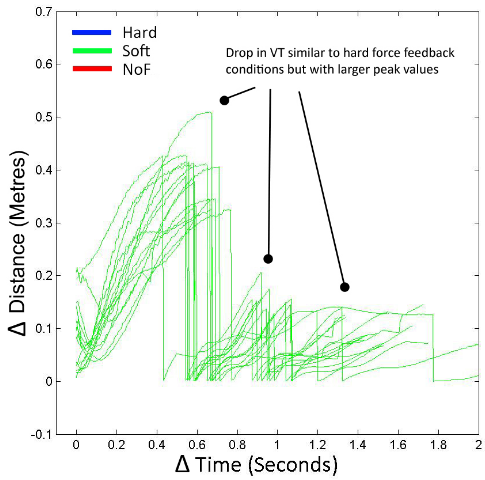


(c) NoF haptic conditions

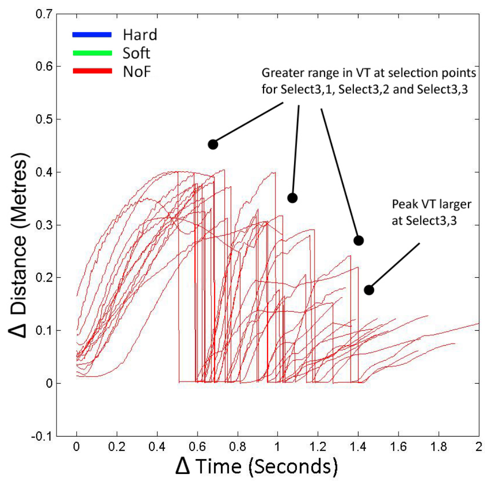
Figure 5.19: Right handed interaction (R-HI), Selection of three targets (Select3), Average VT under hard, soft and NoF haptic conditions



(a) Hard haptic condition

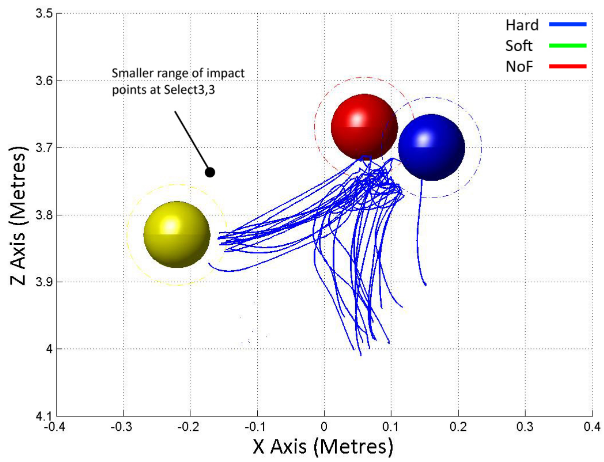


(b) Soft haptic condition

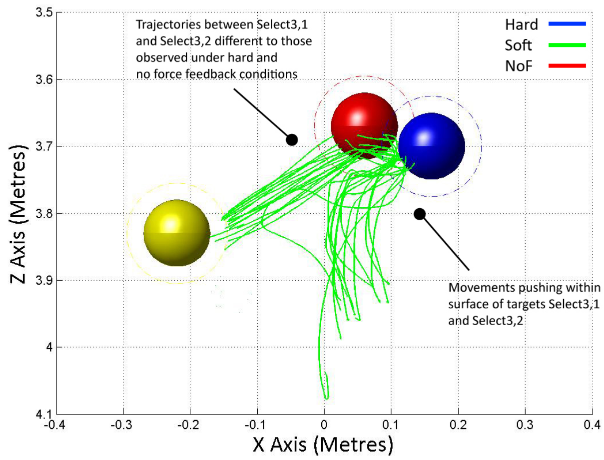


(c) NoF haptic condition

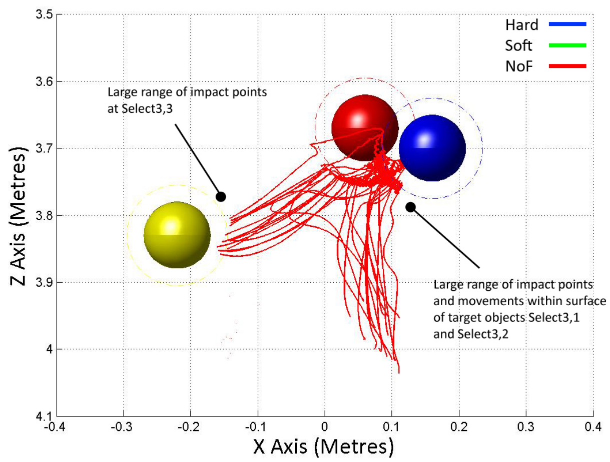
Figure 5.20: Right handed interaction (R-HI), Selection of three targets (Select3), VT profile for task 32 under hard, soft and NoF haptic conditions



(a) Hard haptic condition

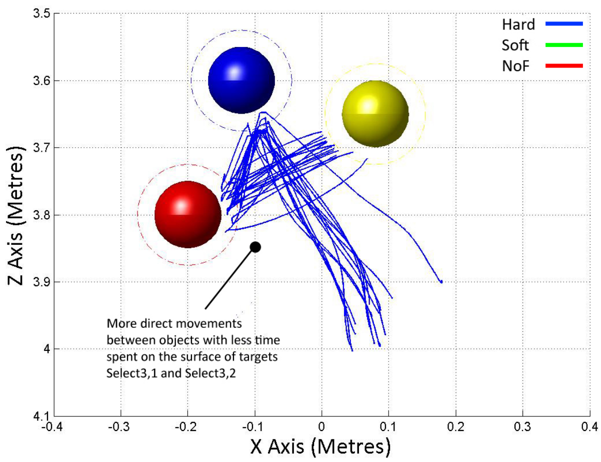


(b) Soft haptic condition

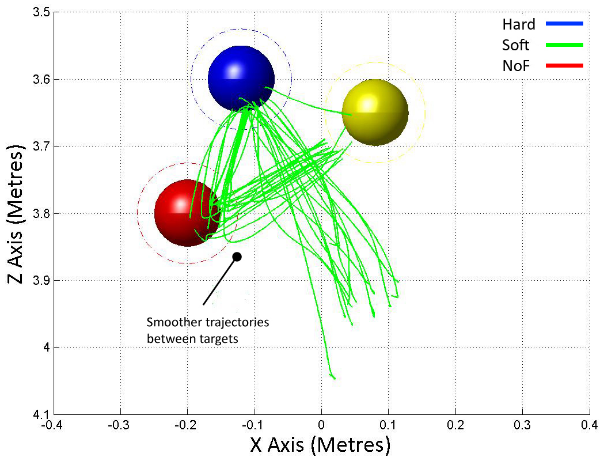


(c) NoF haptic condition

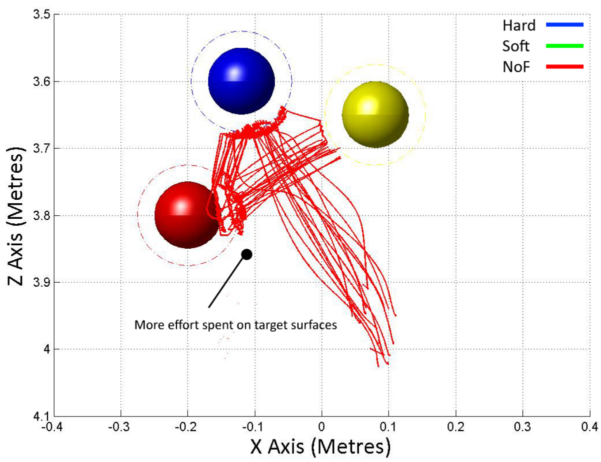
Figure 5.21: Right handed interaction (R-HI), Selection of three targets (Select3), Trajectory ZX profile for task 31 under hard, soft and NoF haptic conditions



(a) Hard haptic condition



(b) Soft haptic condition

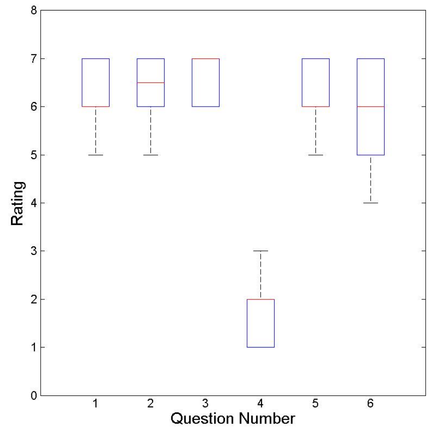


(c) NoF haptic condition

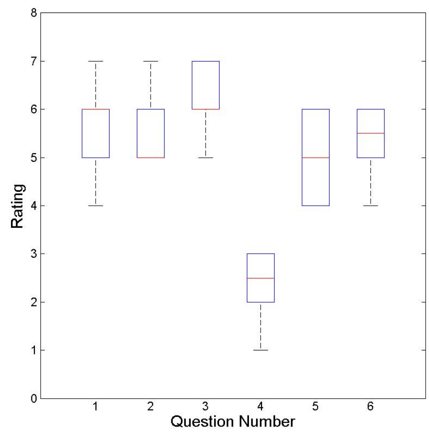
Figure 5.22: Right handed interaction (R-HI), Selection of three targets (Select3), Trajectory ZX profile for task 32 under hard, soft and NoF haptic conditions

Table 5.5: Right Handed Interaction (R-HI)- Summary of significant results between haptic conditions ('x' indicates conditions with significant differences between haptic conditions)

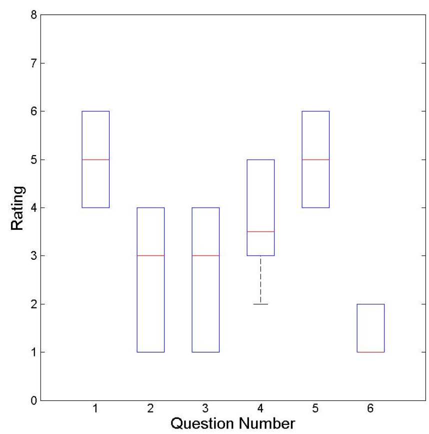
	Sel1	Sel2,1	Sel2,2	Sel,2A	Sel3,1	Sel3,2	Sel3,3	Sel3,A
				MT				
Hard vs NoF					x	x	x	x
Hard vs Soft		x		x			x	x
Soft vs NoF	x							
				DT				
Hard vs NoF			x	x		x	x	
Hard vs Soft						x	x	x
Soft vs NoF	x		x	x	x	x	x	x
				VT				
Hard vs NoF			x	x		x	x	x
Hard vs Soft			x		x	x	x	x
Soft vs NoF			x	x		x	x	x



(a) Hard force feedback responses



(b) Soft force feedback responses



(c) No force feedback responses

Figure 5.23: Right Handed Interaction (R-HI), Usability results between haptic conditions: Questions 1) Was the interaction technique easy to use? (1=Hard to use, 7=Easy to use) 2) Did the interaction feel natural? (1=Not natural, 7=Natural) 3) Was the interaction responsive? (1=Not responsive, 7=Responsive) 4) Did you feel sick? (1=Normal, 7=Sick) 5) During the experiment were you aware of the surroundings outside of the CAVE? (1=Not aware of the outside environment) (7=Very aware of the outside environment) 6) How would you rate the interaction technique? (1=Bad, 7=Good)

condition was selection with hard haptic responses upon contact. In contrast, participants found conditions with no feedback not natural or unresponsive to use. Interestingly, this translated high ratings indicating a greater awareness of the outside surroundings, rather than the IVE itself, indicating perhaps less presence being felt. Altogether, these results suggest that selection with hard and soft haptic feedback led to better usability results than selection without no responses upon contact with the target object.

5.6.5 Discussion

When selecting targets using the right hand only, we found that the strategies taken to complete the task were different for each haptic condition. From the results captured, we found that depending on the type of haptic response presented this would affect the speed of movement and the size of paths taken. Summarised in Table 5.5, we also found that the relationship between MT, DT and VT changed with the number of targets to select. To describe these findings, we present the following behaviour profiles for each haptic condition:

Soft haptic condition:

Table 5.6: Right handed interaction (R-HI), Summary of results, Soft haptic condition

Performance Marker	Result
MT	- Best performing condition for MT and DT. - MT performances for Select1 and Select2 with soft haptic feedback were moderately better compared to performances under hard and NoF conditions. By Select3, there was a large difference in MT between soft and NoF conditions. This indicates that as the number of targets increased so did the separation in performance between selecting targets with soft feedback and without haptic feedback.
DT	- DT performances were significantly better than results achieved when selecting targets providing no force feedback. - Compared to selection with hard force feedback results, we found little difference in DT for Select1 and Select2.
VT	- No difference in VT performance for Select1 between all force feedback conditions. - For Select2 and Select3, soft feedback responses resulted in slower VT compared to selection under NoF conditions. - From velocity profiles, when selecting multiple targets the peak velocities for soft haptic conditions upon selection were smaller compared to selection with no feedback, but greater than those observed for hard force feedback conditions.

Selecting targets with soft force feedback was the best performing condition. This suggests that participants were able to benefit from the haptic feedback experienced upon contact without having to take extended paths to move around targets that acted as physical barrier to subsequent tasks. Interestingly, selecting soft targets led to the best results when selecting multiple targets. As shown by the MT performances for Select1 and Select2, with soft haptic feedback the captured results were only moderately better compared to performances under hard and NoF conditions. By Select3, there was a large difference in MT performance for comparisons between soft and NoF conditions. This indicates that as the number of targets increased so did the separation in performance between selecting targets with soft feedback compared without haptic feedback. By analysing the DT results, we found that by Select3, under soft feedback conditions participants were able to target the shortest paths to task completion compared to selection with hard and no feedback.

With respect to the speed of movement, we found no difference in performance when moving to select a single target between all haptic conditions. When asked to select two or three targets, soft haptic feedback conditions led to slow VT to task completion. However, this decrease in performance did not counter balance the benefit of taking shorter paths taken between targets thus resulting in better movement time to task completion. Furthermore, when selecting multiple targets, we observed key differences in the movements and impact points made between soft and hard haptic conditions. Unlike selection with hard haptic responses, participants were able to benefit from the initial haptic contact upon selection, in addition to continuing their hand motion without abruptly stopping and having to take a longer path to the next target. The range of recorded impact points was smaller under soft haptic conditions compared to selection with no feedback. Against hard haptic conditions, the range of impact points was larger. Altogether, whilst soft haptic feedback reduced the speed of movement between targets, the ratio to the size of paths taken to task completion led to better time taken to task completion.

Hard haptic condition:

Table 5.7: Right handed interaction (R-HI), Summary of results, Hard haptic condition

Performance Marker	Result
MT	- Achieved no significant differences in MT performance for Select1 to results under no and soft force feedback conditions. - For both Select2 and Select3, MT with hard haptic responses was greater than best performing soft force feedback conditions. - For Select3, MT performance under hard haptic conditions was similar to worst performing results achieved when selecting targets that provided no force feedback.
DT	- DT performance under hard haptic conditions for Select1 and Select2 was similar to results when selecting targets with soft feedback responses. - By Select3, larger DT performances were found. Compared to selection under NoF conditions, hard haptic responses achieved smaller DT results to task completion for all target combinations. - Whilst selecting hard targets enabled participants take shorter paths to task completion, when asked to select more than 2 targets selection with soft feedback response achieved better results.
VT	- VT performance was slowest for Select2 and Select3 compared to both soft and NoF conditions. For Select3, we found large drops in VT and slower accelerations curves when moving between targets.

Hard haptic responses did not improve the time taken to select a single or multiple targets. In particular, when selecting multiple targets, results for hard haptic conditions were similar to worst performing results achieved with no force feedback. Whilst the size paths taken to Select1 and Select3 were similar to selection with soft feedback, DT performance was worse when selecting three targets. By analysing the trajectory graphs for Select3, we observed that participants took extended paths to task completion. Compared to selection with soft feedback condition whereby participants could move through objects, under hard feedback conditions they had to stop, manoeuvre around the target, and then proceed towards the new target. Whilst participants were able to select the surface of targets more accurately as shown by the small range of impact points, extra effort was needed to complete the task.

Specifically, under hard haptic conditions VT performance was slowest for Select2 and Select3. As participants had to stop and move around targets, when selecting three targets we found large drops in VT and slower accelerations curves when moving between objects. With the increase in DT and slower VT, this speed to distance ratio resulted in the worst time take results when selecting multiple targets.

NoF haptic condition:

Table 5.8: Right handed interaction (R-HI), Summary of results, NoF haptic condition

Performance Marker	Result
MT	- No difference in MT performance for Select1 between haptic conditions MT was significantly greater under NoF conditions compared to results with soft feedback responses. - By Select3 the MT performance was similar to results recorded for hard haptic conditions.
DT	- Significantly larger DT performances found under NoF conditions compared to results achieved under soft and hard force feedback conditions.
VT	- For Select2 and Select3, VT performance under NoF conditions was best as objects did not provide any feedback to prevent movement upon selection. - From velocity profiles, under NoF conditions larger peak velocities were evident when selecting multiple targets compared to selection with hard and soft feedback.

Selection without haptic feedback led to long paths to task completion. However, when selecting multiple targets, the speed of movement was greater leading to similar results achieved when selecting hard targets. By assessing the trajectory and impact points, we found that with no force feedback participants took extra distance to select the surface of targets and was less accurate. However, as there was no physical impact upon selection, the deceleration between targets was much less. As a result, participants were able to maintain their movement speed between targets to compensate for the extended paths taken to task completion. However, as extra effort was needed to register a selection, when selecting multiple target, no force feedback conditions resulted in the slower MT and DT performances even though VT to task completion was higher.

As found in chapter 4 the relationship between MT, DT and VT changed with haptic condition and the number of targets to select. Whilst participants were able to select the surface of targets with greater accuracy with hard haptic conditions, the speed to distance ratios was such that it led to poor MT performances. Conversely, whilst under NoF conditions participants were able to select objects unimpeded by a physical response, but they found it difficult to register a selection. For Select2 and Select3, and under hard and soft feedback conditions, participants were able to use the presented haptic feedback to take more efficiency paths and achieve task completion with less DT. However, with hard haptic responses, extra effort was needed to move around targets that provided a physical response and upon selection leading to extra DT being taken compared soft feedback conditions.

Besides the size of path taken, velocity was another marker affected by haptic condition. By plotting the velocity profiles, when selecting targets without haptic feedback we found that participants were able to maintain their speed when selecting a single and multiple targets. Under soft and hard haptic conditions, the speed of movement decreased before selection of a target leading to slower VT and in turn MT results. Over multiple targets this led to a significant difference in performance between selection with and without haptic feedback.

To summarise, when selecting targets with the right hand only we found that:

- Selection under soft feedback conditions was the best performing condition
- Selection with haptic feedback led to shorter paths to task completion
- Extra DT was taken under hard haptic conditions compared to selection with soft responses as participants took longer paths to move around objects to task completion.
- The speed of movement between targets was slower when selecting targets with haptic feedback compared to selection without.
- Results demonstrate that different haptic conditions affect the selection behaviour on the target's surface, and in turn overall task efficiency.

5.7 Results- Two Handed Interaction (T-HI)

5.7.1 Selection of One Target (Select1)

5.7.1.1 Movement Time (MT)

When selecting a single target, MT results were the quickest under soft feedback conditions. Shown in Table 5.9, the average MT to task completion under soft haptic conditions compared to selecting targets with hard and no force feedback was slower by 0.088 seconds and 0.139 seconds respectively. Conversely, participants achieved the slowest MT when selecting targets that exerted no feedback. With respect to the standard deviation results, the differences in MT between all three haptic conditions were at most greater than 1. Therefore, this suggests that haptic feedback did not affect MT when selecting a single target.

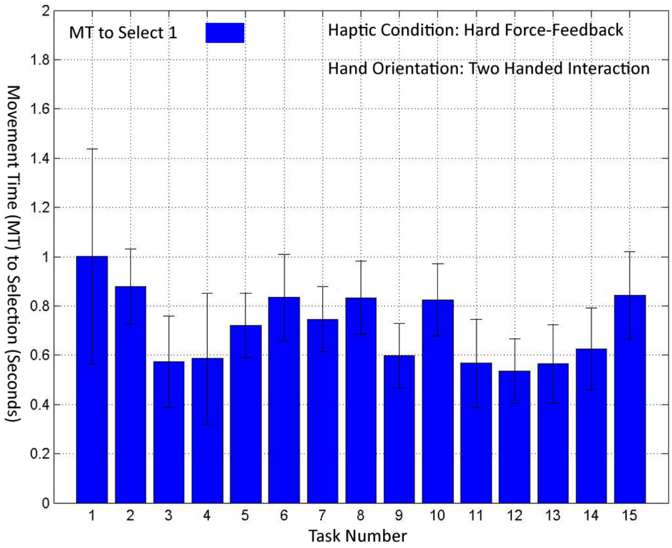
Confirming this trend, the computed ANOVA results also show only a few tasks where MT performance was significantly different between conditions. Shown in Table 5.9 for Select1, we found only 1 task where the average MT behaviour under a hard force feedback condition was significantly different to the results captured under both soft and no force feedback conditions. For MT comparisons between soft and no feedback conditions, we only observed 4 tasks whereby participants performed better selecting soft targets that led to p values less than 0.05. As these values were not large, this suggests that both hard and soft feedback did not greatly affect MT performance.

5.7.1.2 Distance Travelled (DT)

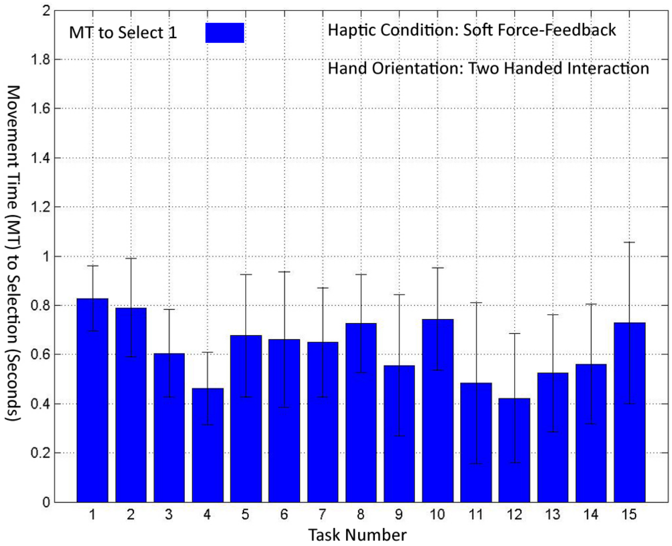
On average, participants took the least DT under no haptic feedback conditions. From Figure 5.24, in contrast, selection with soft feedback responses lead to the largest average DT to task completion. Shown in Table 5.9, the average DT under NoF conditions compared to selection with hard and soft haptic

Table 5.9: Two Handed Interaction (T-HI), Selection of one target (Select1), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

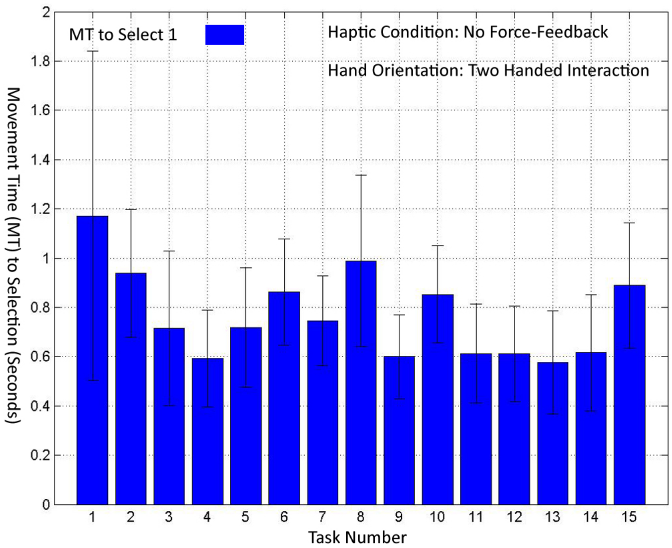
Average Performance				
Haptic condition:	MT	DT	VT	
			Right hand	Left hand
Hard	0.716	0.21	0.124	0.182
Soft	0.627	0.248	0.161	0.124
NoF	0.766	0.18	0.176	0.159
Standard Deviation				
Haptic condition:	MT	DT	VT	
			Right hand	Left hand
Hard	0.147	0.092	0.105	0.131
Soft	0.124	0.099	0.1	0.114
NoF	0.178	0.086	0.112	0.124
Number of tasks whereby difference between haptic conditions achieved p values < 0.05				
Hard vs NoF	0	2		
Hard vs Soft	1	1		
Soft vs NoF	4	0		



(a) Hard haptic conditions

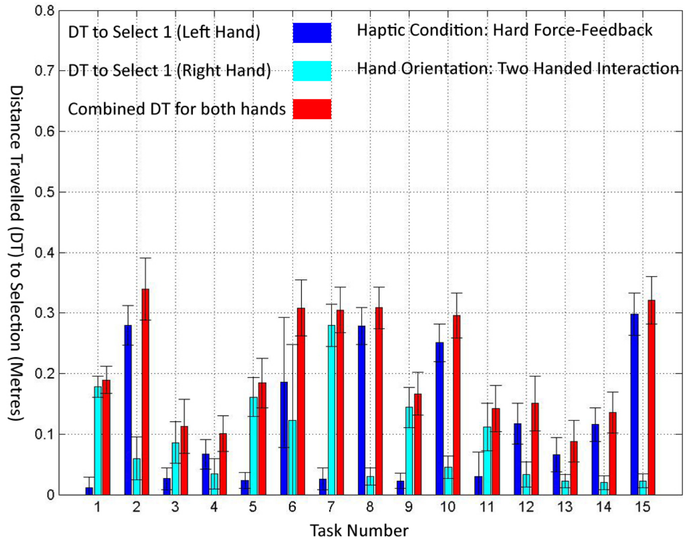


(b) Soft haptic conditions

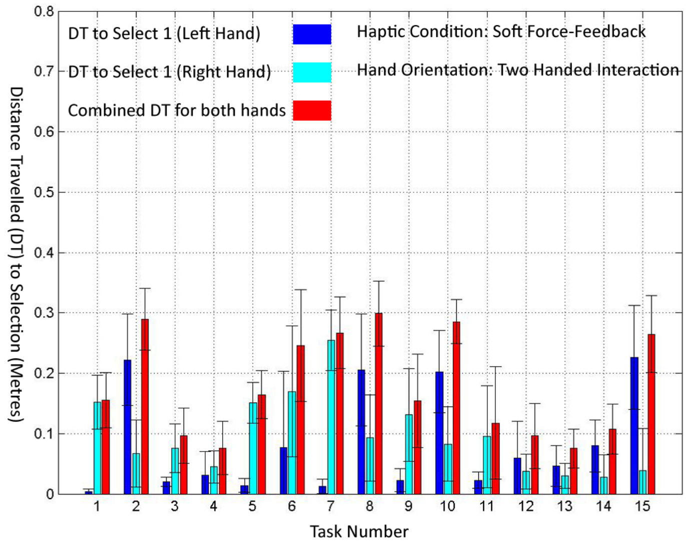


(c) NoF haptic conditions

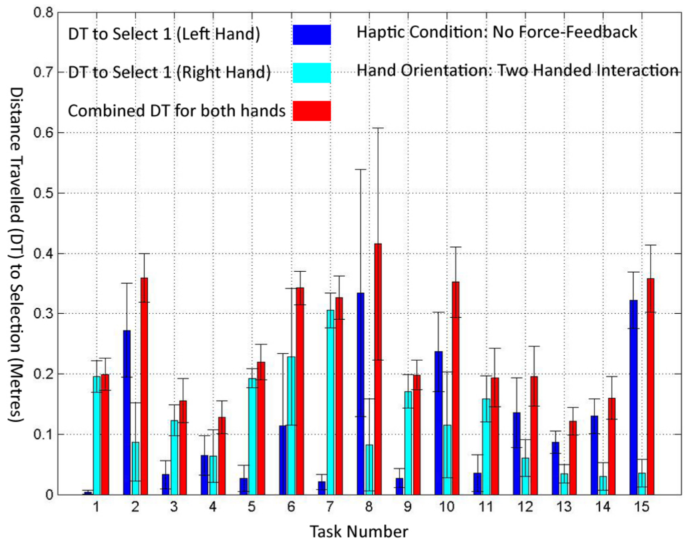
Figure 5.24: Two handed interaction (T-HI), Selection of one target (Select1), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

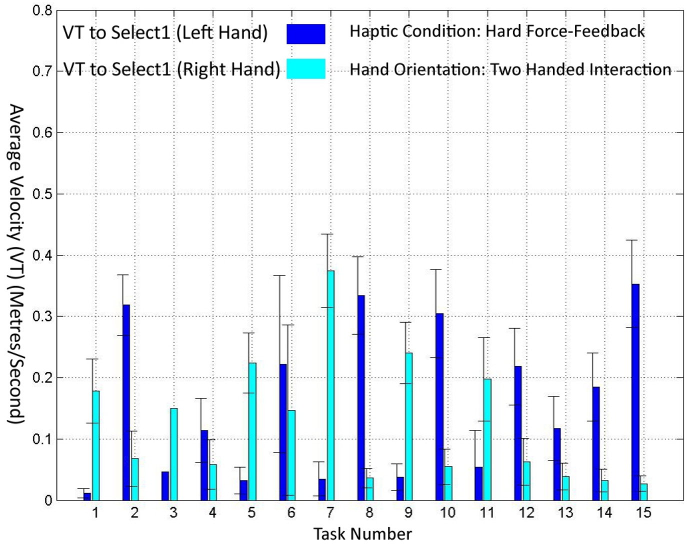


(b) Soft haptic conditions

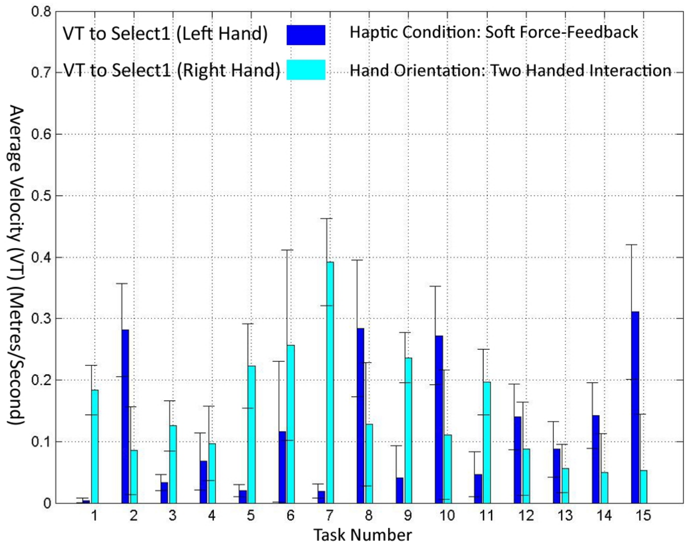


(c) NoF haptic conditions

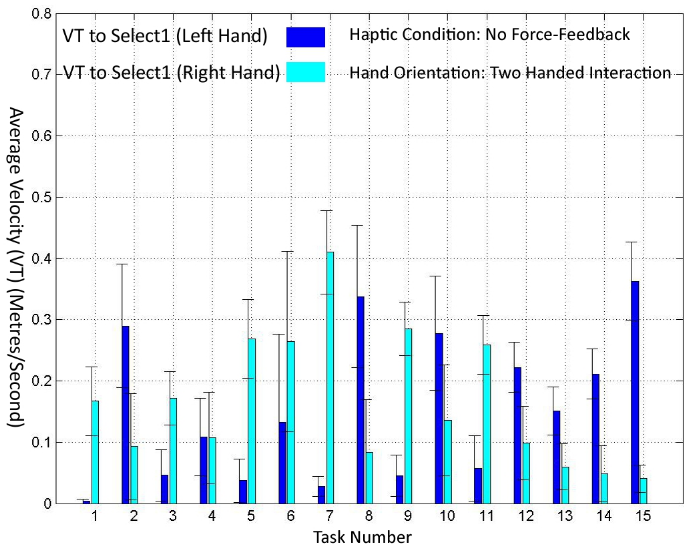
Figure 5.25: Two handed interaction (T-HI), Selection of one target (Select1), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

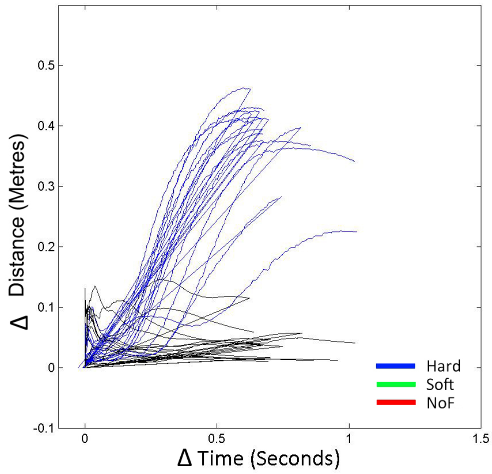


(b) Soft haptic conditions

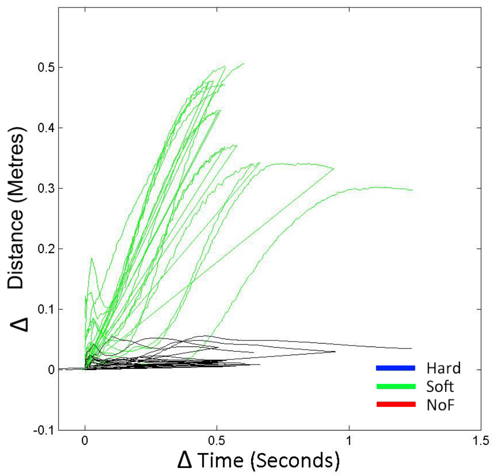


(c) NoF haptic conditions

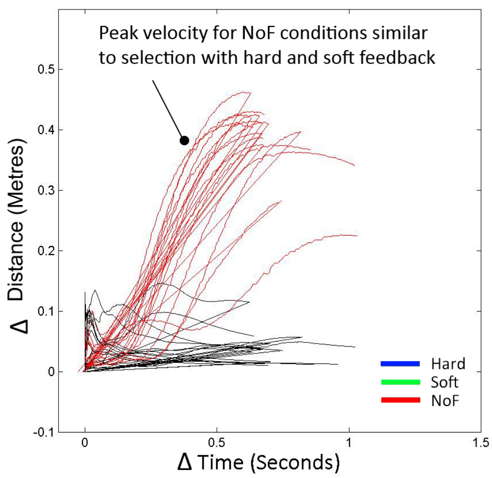
Figure 5.26: Two handed interaction (T-HI), Selection of one target (Select1), Average VT under hard, soft and NoF haptic conditions



(a) Hard haptic condition

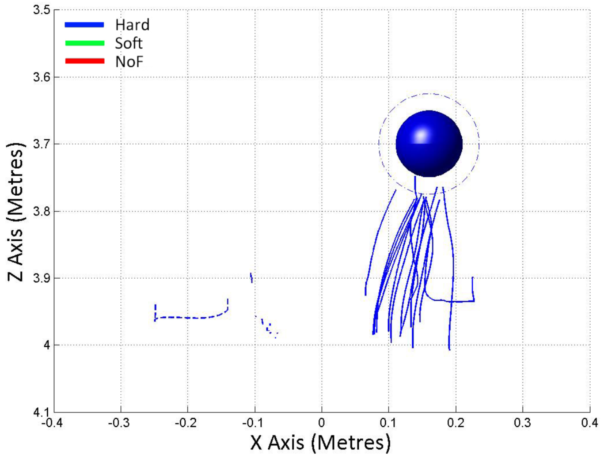


(b) Soft haptic condition

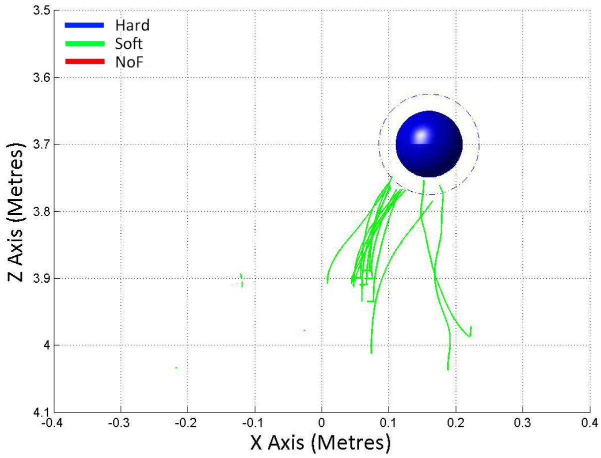


(c) NoF haptic condition

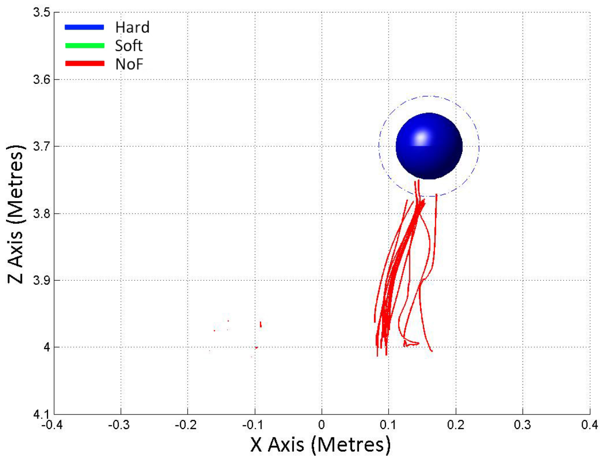
Figure 5.27: Two handed interaction (T-HI), Selection of one target (Select1), VT profile for task 7 under hard, soft and NoF haptic conditions (black line - movement with the left hand)



(a) Hard force feedback responses

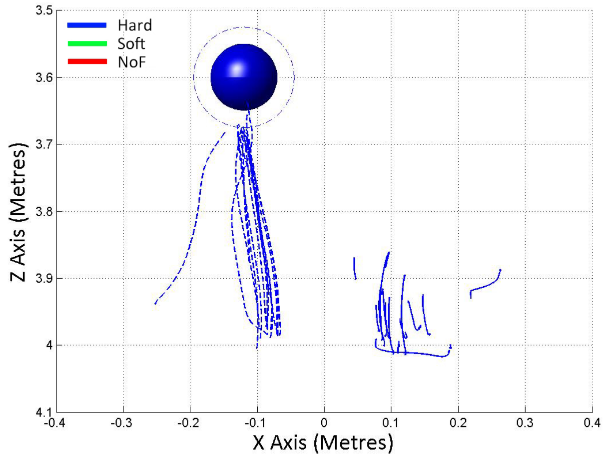


(b) Soft force feedback responses

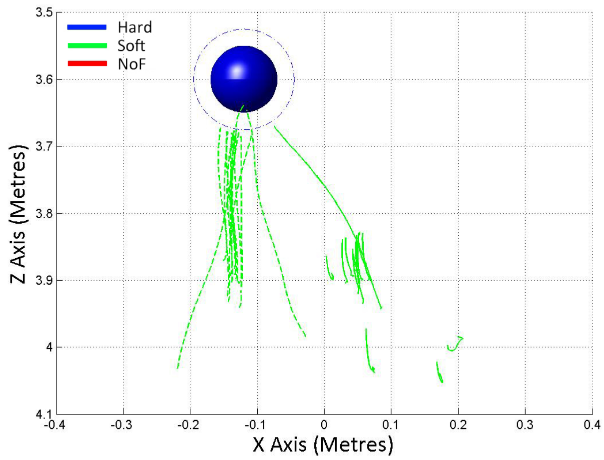


(c) No force feedback responses

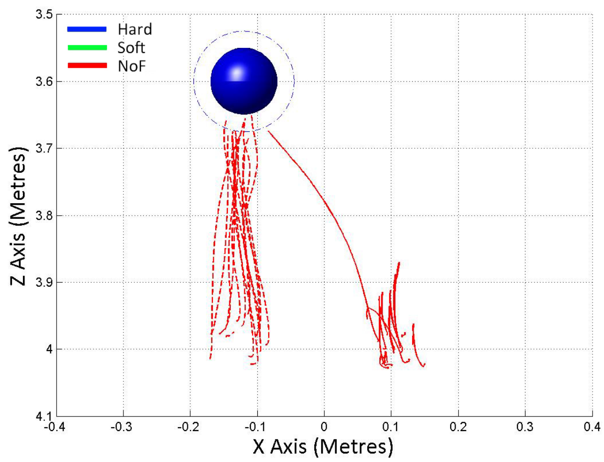
Figure 5.28: Two handed interaction (T-HI), Selection of one target (Select1), Trajectory ZX profile for task 1 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)



(a) Hard haptic conditions

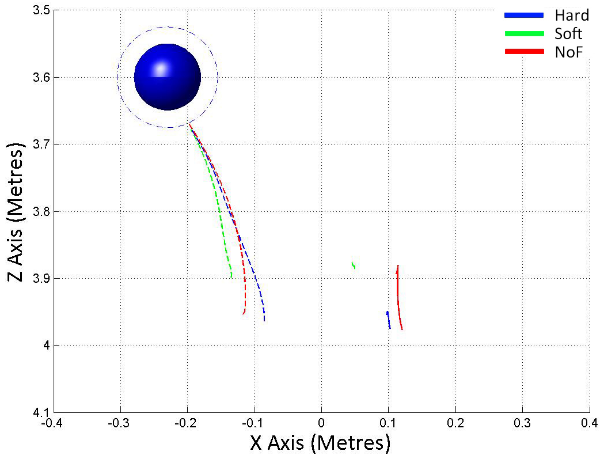


(b) Soft haptic conditions

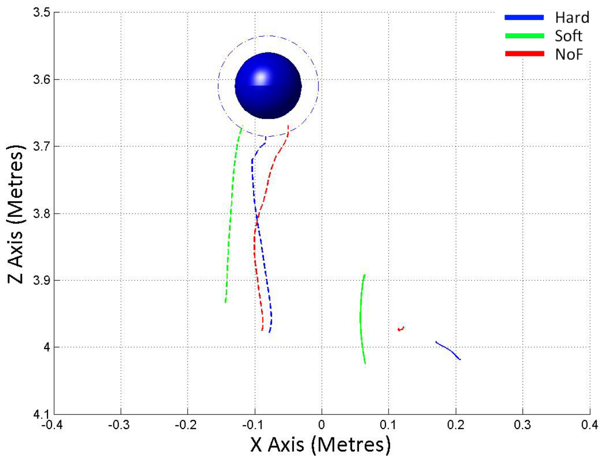


(c) NoF haptic conditions

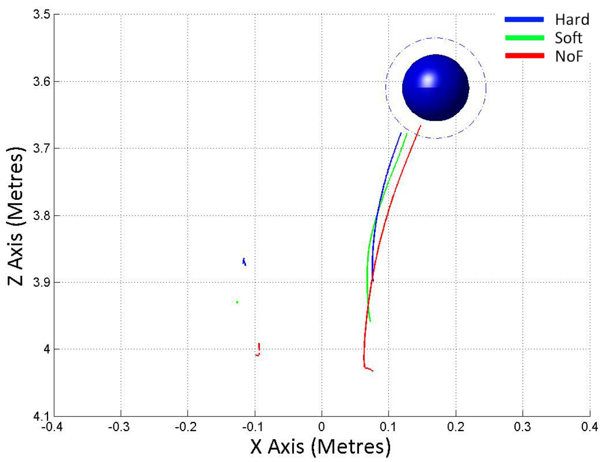
Figure 5.29: Two handed interaction (T-HI), Selection of one target (Select1), Trajectory ZX profile for task 2 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)



(a) Task 8, participant 7



(b) Task 10, participant 10



(c) Task 7, participant 14

Figure 5.30: Two handed interaction (T-HI), Selection of one target (Select1), Trajectory ZX profile for tasks 7, 8 and 10 demonstrating differences in handedness (dashed line - movement with the left hand)

feedback was smaller by 0.038m and 0.069m respectively. Nevertheless, from the standard deviation results these variations between all three haptic feedback conditions were small. Therefore, this suggests that haptic feedback did not affect DT performance to task completion.

By assessing the computed ANOVA results, these results showed only a few variations in DT performance between the evaluated haptic force feedback conditions. From Table 5.9, this showed a low number of recorded tasks where the captured DT was significantly different between haptic conditions. At most we observed 2 tasks from 15 when selecting a single target with no force feedback had a smaller DT in comparison to when then selecting targets with a hard feedback. Furthermore, coupled with the average and standard deviation results, this shows that when selecting a single target with two hands haptic feedback did not affect DT behaviour.

5.7.1.3 Velocity Taken (VT)

When selecting a single target, participants completed the task with the quickest VT under no force feedback conditions. In contrast, from Figure 5.26, selection with hard targets resulted in the slowest VT results. From Table 5.9, the combined average VT for both hands under NoF conditions compared to selection with hard and soft feedback was faster by 0.118m/s and 0.036m/s respectively. For differences in VT between haptic feedback conditions, selection under hard conditions was faster by 0.011m/s. With respect to the standard deviation results differences between all haptic conditions were less than 1. Therefore, this suggests that haptic feedback had little effect on the VT taken to select a single target.

To assess this further we plotted a set of velocity profiles. Shown in Figure 5.27, the peak velocities and acceleration curves achieved for each condition were similar between all force feedback conditions. Furthermore, these plots also showed that only one hand, either the right or left hand are used during the selection process. Therefore, these results are similar to selecting with one hand only with the added benefit of choosing the best physical orientation to perform the presented selection target.

By assessing Figure 5.26, we were able to analyse the hand dominance for the task. For each haptic condition, we found a even split where participants selected 6 targets predominately using their right and 7 whilst using their left. This trend was consistent for each of the haptic conditions, suggesting that handedness of interaction are not affected by haptic feedback.

5.7.1.4 Trajectory Analysis

By plotting the trajectory maps of the gestures used to selection, we analysed the ballistic movements used to task completion. As shown in Figures 5.28 and 5.29, for the majority tasks, we found that participants used similar arching movements and impact points for all three haptic conditions. In particular, as the same face of the object target was used for selection, this further suggests that different haptic feedback conditions did not affect the selection strategy for this difficulty class.

Furthermore, by assessing the single trajectory maps overlaid with each haptic condition, we can see that the hand dominance was mainly affected by the position of the target. As we can see in Figure 5.30, predominately, the left hand was used when the target was placed closer an within the left workspace, and conversely participants used their right hand when the target was in the right workspace. As this was consistent for each haptic feedback condition this suggests that participants consider hand combinations best suited to the task presented.

5.7.2 Selection of Two Targets (Select2)

5.7.2.1 Movement Time (MT)

MT to task completion was quickest under soft feedback conditions. From Table 5.10, the average MT for Select2,All under soft feedback conditions compared to selection with hard and no responses was smaller by 0.130 seconds and 0.214 seconds respectively. With respect to differences between hard and NoF conditions, participants selected targets with hard responses 0.083 seconds faster. These differences in MT between hard and soft, and soft and NoF haptic conditions was greater than 2 standard deviations. Comparisons between hard and NoF haptic conditions was greater than 1. As a result, these findings suggest that soft haptic feedback conditions led to the smallest MT to task completion.

With respect to the individual sub-tasks, we can see that for both Select2,1 and Select2,2, participants performed best under soft feedback conditions. Shown in Figure 5.31, there was a noticeable difference in MT between all three haptic conditions for Select2,1 in contrast to Select2,2. From Table 5.10, the difference in MT for Select2,1 between all three haptic conditions was: (Hard-NoF), -0.052 seconds; (Hard-Soft), 0.099 seconds; and (Soft-NoF), -0.152 seconds. Conversely, the differences in MT for Select2,2 were smaller: (Hard-NoF), -0.031 seconds; (Hard-Soft), 0.031 seconds; and (Soft-NoF), -0.062 seconds. This suggests that when selecting a single target with two hands, haptic feedback had an effect on MT to the first target.

Nevertheless, by comparing these differences with the computed ANOVA results, we did not record many tasks suggesting an interaction between haptic feedback and overall MT performance. From Table 5.10, at most for all sub-tasks we recorded only 1 task where the difference in MT between haptic feedback conditions led to a p value less than 0.05. Therefore, whilst we observed differences in MT when moving to the first target, these findings indicated that haptic feedback did not affect performance.

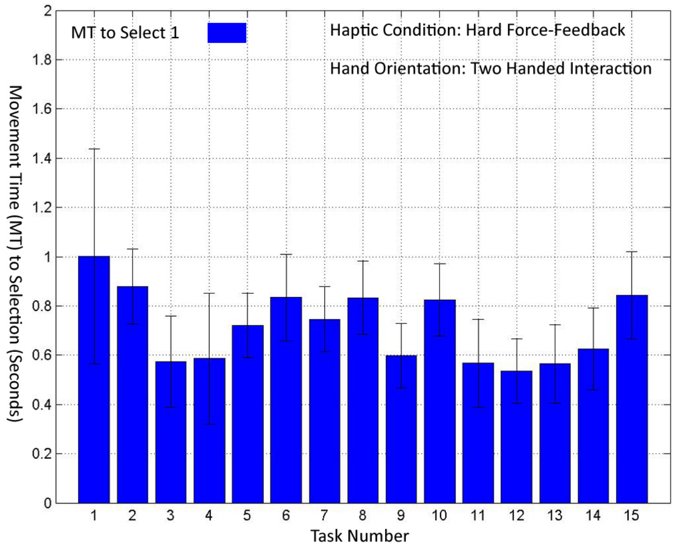
5.7.2.2 Distance Travelled (DT)

When selecting two targets, the shortest DT was achieved under hard feedback conditions. From Table 5.10, in comparison to results captured under no and soft feedback conditions, the average DT to task completion was shorter by 0.193m and 0.078m respectively. Conversely, participants took the longest path when selecting targets that exerted no feedback. For hard and soft feedback responses, we found that both of these results were greater than 3 standard deviations in comparison to selecting Select2,All with no feedback. For differences between hard and soft conditions this was much less showing little effect on DT. Therefore, this suggests that hard haptic conditions led to shorter DT when selecting two targets using bi-manual interaction.

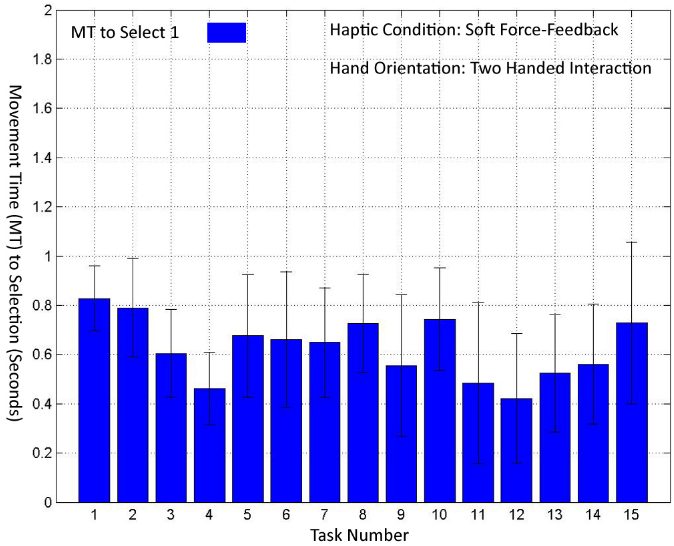
For the individual subtasks, we found that the trend observed for task completion also continued. In Table 5.10, for both Select2,1 and Select2,2 the shortest paths were achieved under a hard feedback condition, whereas we recorded the longest DT under no feedback conditions. Ultimately, for both the first and second target, the performance gap between hard and soft feedback, and selecting with no feedback was on average 0.100m. This demonstrates that the trajectory used when selecting with both

Table 5.10: Two Handed Interaction (T-HI), Selection of two targets (Select2), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

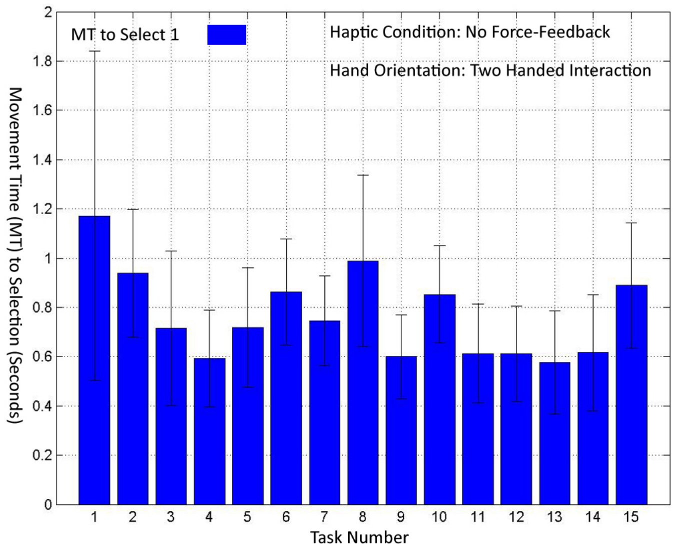
Average Performance			
Haptic condition:	MT		
	Select2,1	Select2,2	Select2,All
Hard	0.806	0.254	1.06
Soft	0.707	0.223	0.93
NoF	0.859	0.285	1.143
	DT		
Hard	0.28	0.044	0.325
Soft	0.345	0.059	0.405
NoF	0.444	0.129	0.572
	VT		
Hard (Right Hand)	0.178	0.105	0.141
Soft (Right Hand)	0.157	0.177	0.167
NoF (Right Hand)	0.199	0.401	0.3
Hard (Left Hand)	0.168	0.169	0.168
Soft (Left Hand)	0.128	0.168	0.148
NoF (Left Hand)	0.165	0.297	0.231
Standard Deviation			
Haptic condition:	MT		
	Select2,1	Select2,2	Select2,All
Hard	0.159	0.103	0.147
Soft	0.139	0.093	0.132
NoF	0.153	0.123	0.178
	DT		
Hard	0.096	0.037	0.111
Soft	0.066	0.033	0.088
NoF	0.081	0.142	0.181
	VT		
Hard (Right Hand)	0.077	0.06	0.069
Soft (Right Hand)	0.074	0.075	0.075
NoF (Right Hand)	0.073	0.227	0.15
Hard (Left Hand)	0.058	0.102	0.08
Soft (Left Hand)	0.061	0.087	0.074
NoF (Left Hand)	0.057	0.133	0.095
Number of tasks whereby difference between haptic conditions achieved p values < 0.05			
Haptic condition:	MT		
	Select2,1	Select2,2	Select2,All
Hard vs NoF	1	1	1
Hard vs Soft	1	0	1
Soft vs NoF	1	1	1
	DT		
Hard vs NoF	3	10	8
Hard vs Soft	7	0	5
Soft vs NoF	8	10	11



(a) Hard haptic conditions

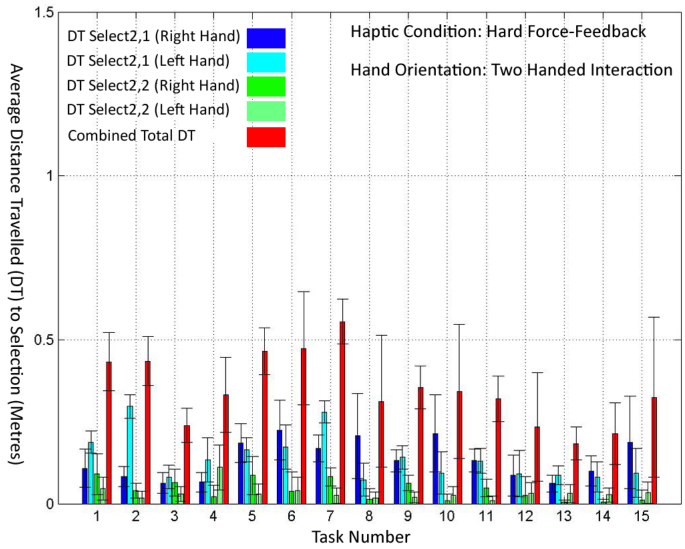


(b) Soft haptic conditions

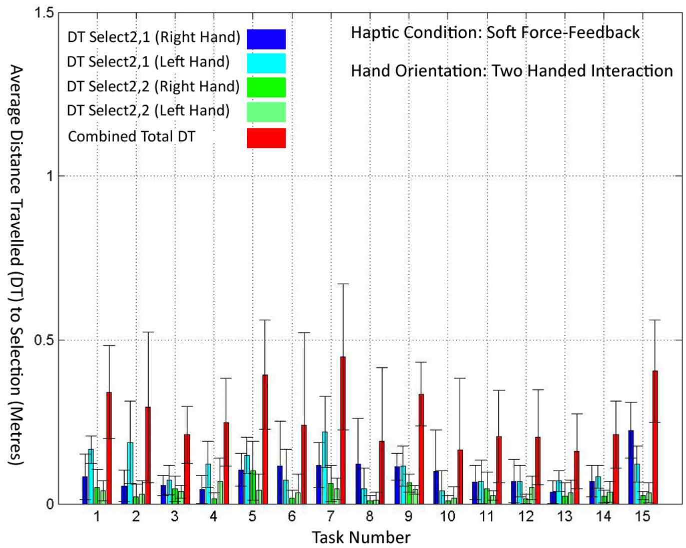


(c) NoF haptic conditions

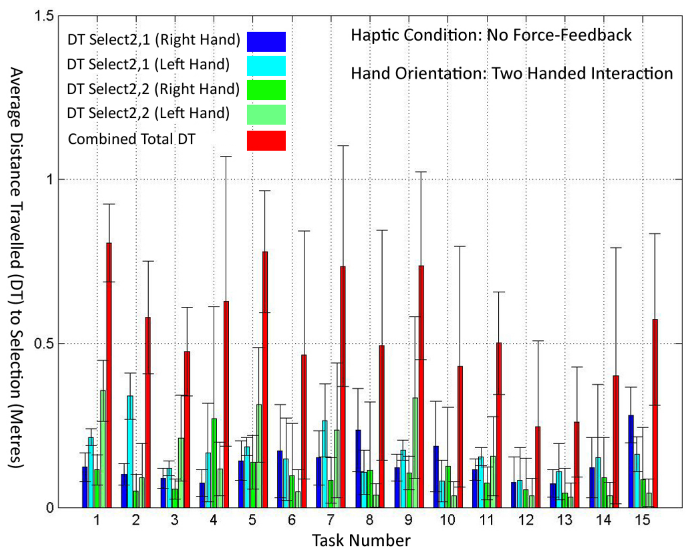
Figure 5.31: Two handed interaction (T-HI), Selection of one target (Select1), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

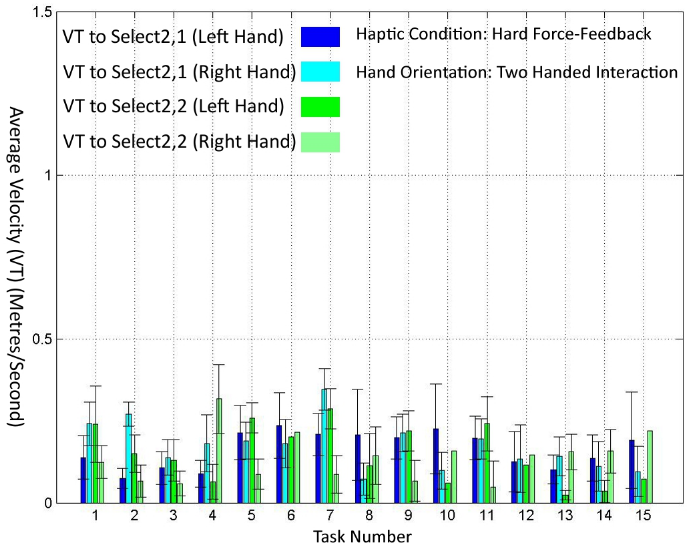


(b) Soft haptic conditions

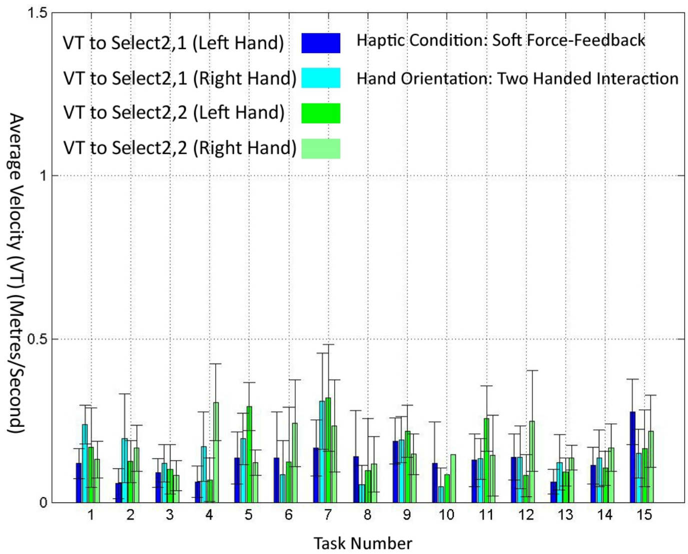


(c) NoF haptic conditions

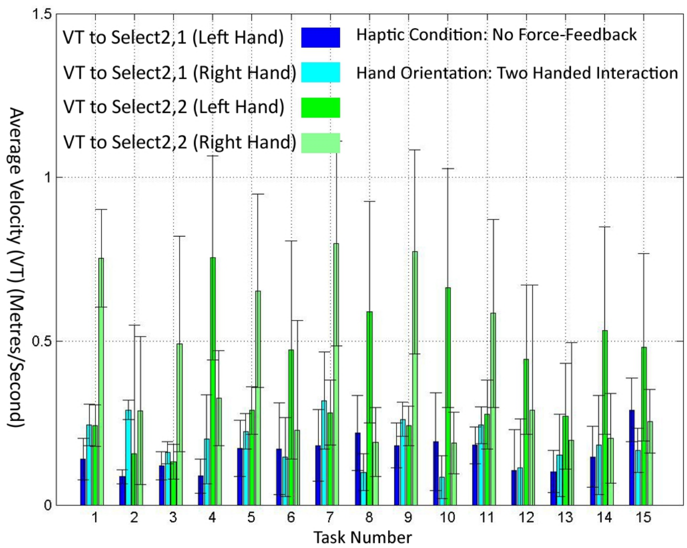
Figure 5.32: Two handed interaction (T-HI), Selection of two targets (Select2), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

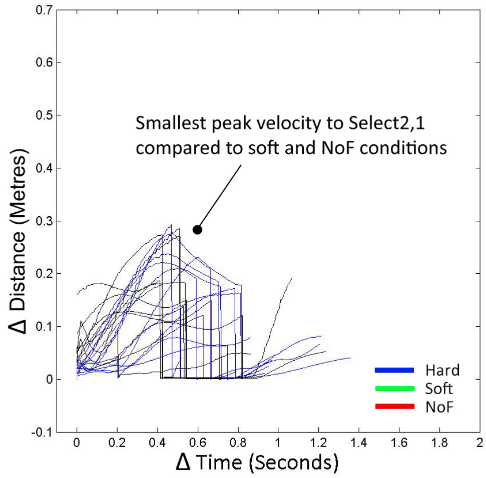


(b) Soft haptic conditions

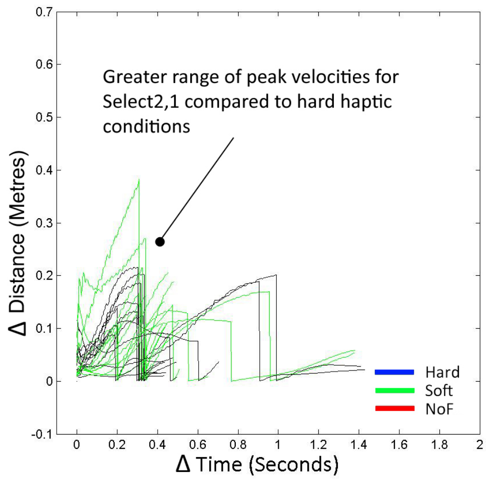


(c) NoF haptic conditions

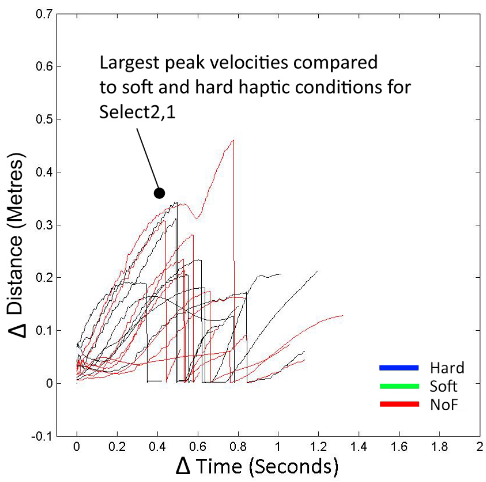
Figure 5.33: Two handed interaction (T-HI), Selection of two targets (Select2), Average VT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

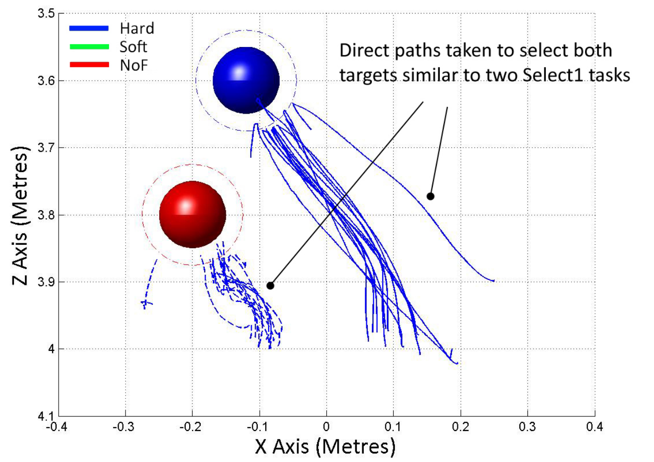


(b) Soft haptic conditions

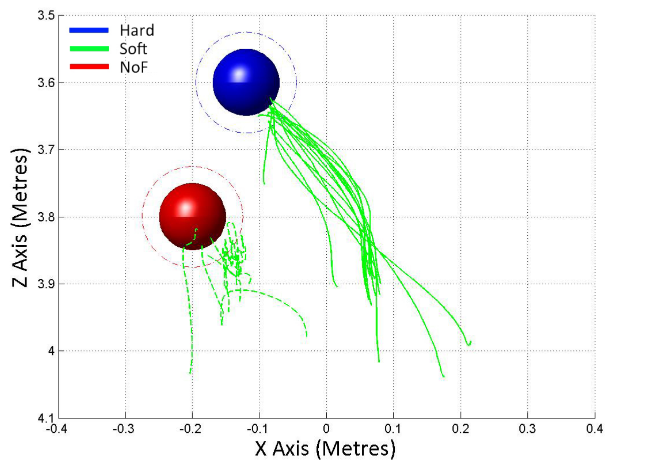


(c) NoF haptic conditions

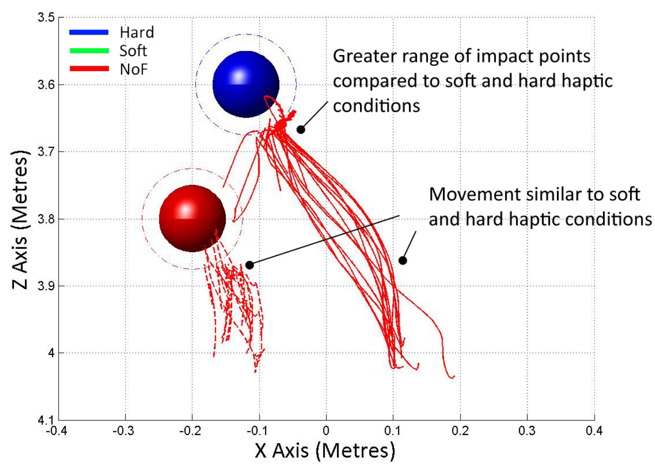
Figure 5.34: Two handed interaction (T-HI), Selection of two targets (Select2), VT profile for task 7 under hard, soft and NoF haptic conditions (black line - movement with the left hand)



(a) Hard haptic conditions

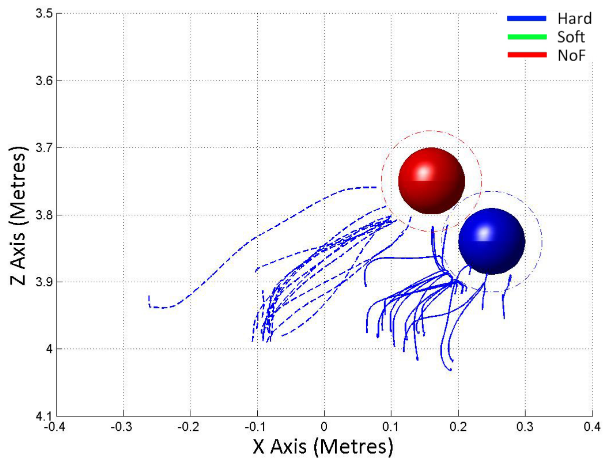


(b) Soft haptic conditions

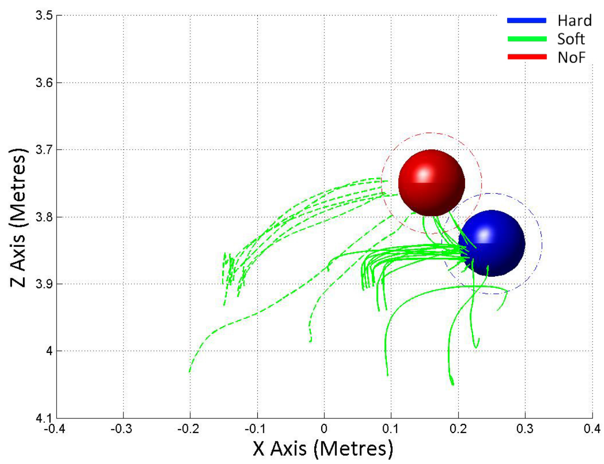


(c) NoF haptic conditions

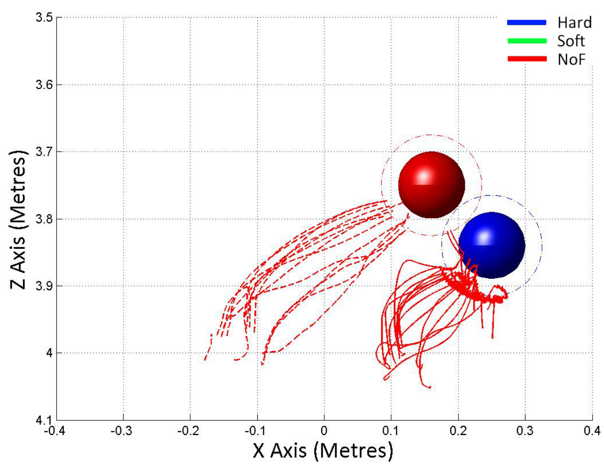
Figure 5.35: Two handed interaction (T-HI), Selection of two targets (Select2), Trajectory ZX profile for task 17 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)



(a) Hard haptic conditions



(b) Soft haptic conditions



(c) NoF haptic conditions

Figure 5.36: Two handed interaction (T-HI), Selection of two targets (Select2), Trajectory ZX profile for task 18 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)

haptic feedback conditions is more efficient in comparison to selecting with no feedback responses.

From the ANOVA results, we can see that the DT results for both hard and soft conditions are significantly different to when there is no feedback for most tasks. Interestingly, we noticed differences in behaviour between DT performance to the first and second targets. Shown in Table 5.10, for Select2,2 and Select2,All, the number of tasks where DT was better for hard and soft feedback conditions in comparison to selecting with no feedback was greater than 8 tasks. In contrast, when selecting the first target, we found at most 8 tasks. Furthermore, we found that the DT taken to Select2,1 between soft and hard conditions were also quite different. This suggests that movement to the first target was affected by haptic condition, which then influenced the path taken to the second target.

In terms of handedness of interaction, participants selected targets equally using both the left and right hand. From Figure 5.32, depending on the task and thus orientation of the targets, participants used the best left and right hand combination to complete the task. This is an interesting result, as considering that all participants were quoted to being right handed, the results show that this was not the dominant factor. Furthermore, as this was consistent for each haptic condition this suggests that haptic force feedback did not affect handedness of interaction.

5.7.2.3 Velocity Taken (VT)

VT to task completion was highest when selecting targets under NoF conditions. Shown in Figure 5.33, we found participants used two hands, using a right and left combination to best select the subtasks. From Table 5.10, the combined average VT for both hands under NoF conditions was 0.266m/s. The difference in VT selecting targets with hard and soft feedback compared to selection without haptic feedback was slower by 0.163m/s and 0.108m/s respectively. The difference between hard and soft feedback conditions was small, whereby selection under soft feedback conditions was faster by 0.003m/s. With respect to the standard deviation results, comparisons between feedback conditions were within 1. This suggests that selection without haptic feedback leads to a small benefit in VT performance.

In terms of the sub-tasks, VT performance under NoF feedback conditions was faster when moving to the second target. From Table 5.10, for Select2,2 the difference in VT under NoF conditions compared to selection with hard and soft feedback responses was quicker by 0.233m/s and 0.177m/s respectively. In contrast, the difference between haptic feedback conditions was small with 0.036m/s. Therefore, these findings indicated that movement to the second target was faster under NoF conditions.

To assess this further we plotted the selection profiles. As shown in Figure 5.34, whilst the acceleration to the second target was slower in both hard and soft feedback conditions, in contrast for when there is no feedback participants were able to move more quickly. As a result participants were able to retain greater speed throughout the task without the hindrance of force feedback upon selection.

5.7.2.4 Trajectory Analysis

From the trajectory maps, we can see that by using bi-manual interaction, participants were able to use both the left and right hands in a sequence that reduced the difficulty of the task. As shown in Figures 5.35 and 5.36, we can see examples where a single hand was not used to select both targets. By doing so, participants were able to eliminate the interaction effects of haptic feedback on the surface of the object.

Ultimately, this behaviour meant there was little difference in selection performance between soft, hard and NoF haptic conditions.

5.7.3 Selection of Three Targets (Select3)

5.7.3.1 Movement Time (MT)

Participants completed the selection of all three targets the quickest MT under soft feedback. In comparison, from Table 5.11 the average MT to task completion under hard and NoF conditions was slower by 0.197 seconds and 0.277 seconds. For difference in MT between haptic feedback conditions, selection with soft responses was faster by 0.197 seconds to hard feedback conditions. These differences in MT between all feedback conditions were within 1 standard deviation. Therefore, this suggests that haptic feedback had a little effect on MT to task completion.

With respect to the individual sub-tasks, for Select3,1 and Select3,2 the average MT was quickest under soft feedback conditions. Shown in Figure 5.37, the biggest difference in MT occurred at Select3,1, levelling out progressing across the other two sub-tasks. Interestingly, for Select3,3, the quickest MT was achieved under NoF conditions. Besides MT to the first target, the differences between haptic conditions were small and within 1 standard deviation. Therefore, again this suggest that haptic feedback did not affect MT when selecting three targets with bi-manual interaction except for movement to the first target.

By analysing the ANOVA results, we evaluated the extent to which the MT differences were significant. Again, as the variations from the second target onwards were small, the MT behaviour between the three conditions were similar. In contrast, for Select3,1 we found a few tasks suggesting that the MT for no feedback was significantly different in comparison to hard and soft conditions. Furthermore, as the MT to the first target was much greater than Select3,2 and Select3,3, this also suggests MT behaviour is affected by the number of targets. Nevertheless, as we found at most 5 out of 15 tasks where the p values were less than 0.05, this only indicates a potential interaction. Therefore, for selection of three targets the haptic feedback did not affect MT behaviour when selecting targets with two hands. This is in contrast to the results captured when selecting with the right hand only.

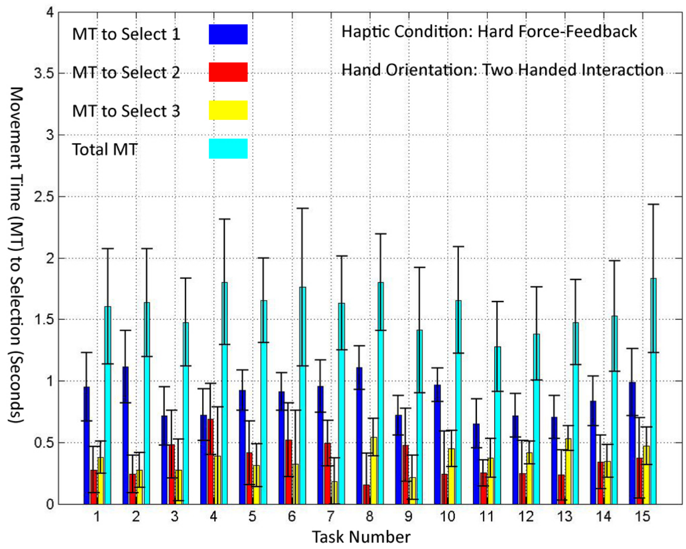
5.7.3.2 Distance Travelled (DT)

Participants on average took the shortest DT under soft and hard feedback conditions. Shown in Figure 5.38, the worst performing condition was selection under with no force feedback. From Table 5.11, the average difference in DT to task completion under hard and soft feedback compared to selection with NoF conditions was smaller by 0.164m and 0.128m respectively. For both selection with hard and soft haptic feedback to NoF conditions, DT was greater than 2 standard deviations. In comparison, for DT results achieved under soft conditions against hard this was just over 1. These results suggest that soft hand and no force feedback responses led to smaller DT results.

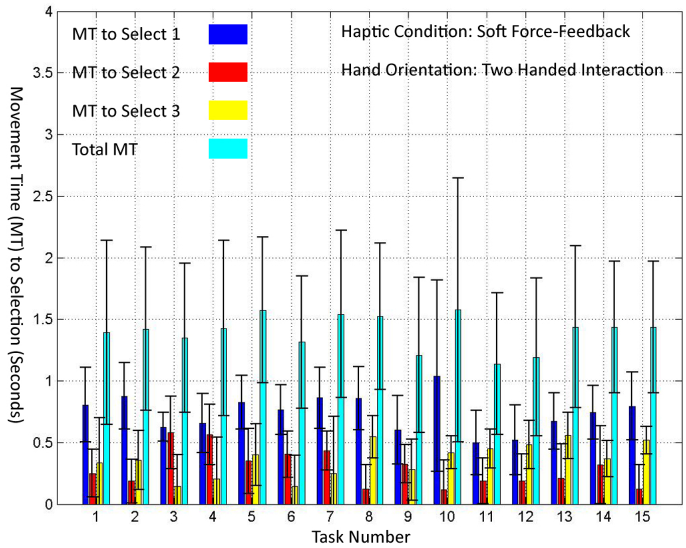
With respect to the sub-tasks, selection with haptic feedback improved DT performance to second target. Shown in Figure 5.38, the least DT was taken for all three haptic conditions for Select3,2 increasing by Select3,3. With respect to differences in DT, selection under hard and soft feedback conditions compared to selection without force feedback was smaller by 0.174m and 0.180m respectively. This

Table 5.11: Two Handed Interaction (T-HI), Selection of three targets (Select3), Average, Standard deviation and ANOVA results for MT, DT and VT (n=10 for each haptic condition)

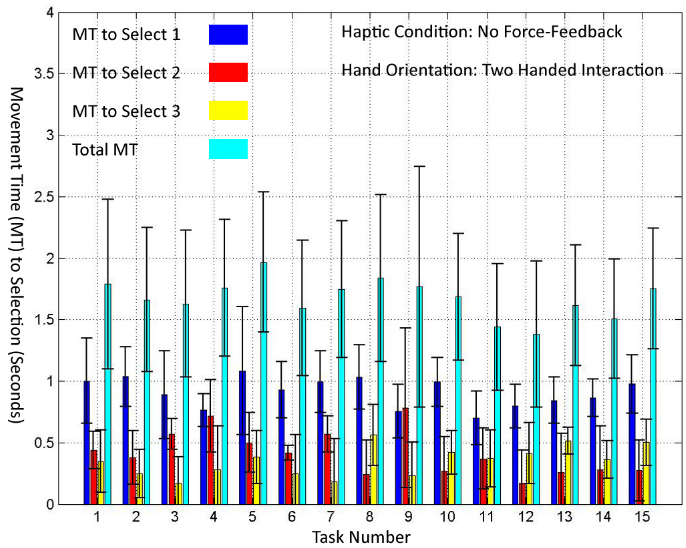
Average Performance				
Haptic condition:	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard	0.866	0.363	0.366	1.595
Soft	0.743	0.291	0.364	1.398
NoF	0.911	0.416	0.349	1.675
	DT			
Hard	0.417	0.091	0.152	0.659
Soft	0.385	0.058	0.195	0.637
NoF	0.454	0.225	0.373	1.052
	VT			
Hard (Right Hand)	0.191	0.109	0.109	0.136
Soft (Right Hand)	0.186	0.171	0.134	0.164
NoF (Right Hand)	0.215	0.376	0.312	0.301
Hard (Left Hand)	0.163	0.119	0.117	0.133
Soft (Left Hand)	0.144	0.193	0.149	0.162
NoF (Left Hand)	0.162	0.276	0.402	0.28
	Standard Deviation			
Haptic condition:	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard	0.152	0.147	0.105	0.167
Soft	0.147	0.152	0.137	0.136
NoF	0.119	0.18	0.122	0.154
	DT			
Hard	0.09	0.043	0.045	0.091
Soft	0.09	0.041	0.053	0.108
NoF	0.1	0.125	0.113	0.167
	VT			
Hard (Right Hand)	0.067	0.056	0.056	0.059
Soft (Right Hand)	0.074	0.094	0.079	0.082
NoF (Right Hand)	0.069	0.216	0.139	0.142
Hard (Left Hand)	0.074	0.079	0.047	0.067
Soft (Left Hand)	0.08	0.153	0.088	0.107
NoF (Left Hand)	0.081	0.152	0.171	0.135
Number of tasks whereby difference between haptic conditions achieved p values < 0.05				
Haptic condition:	MT			
	Select3,1	Select3,2	Select3,3	Select3,All
Hard vs NoF	4	1	0	1
Hard vs Soft	1	1	0	0
Soft vs NoF	5	5	0	0
	DT			
Hard vs NoF	5	7	7	3
Hard vs Soft	3	12	12	15
Soft vs NoF	7	13	13	15



(a) Hard haptic conditions

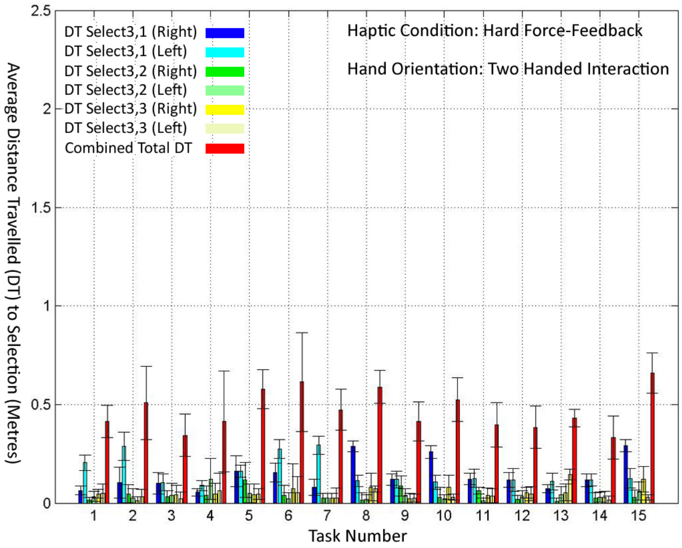


(b) Soft haptic conditions

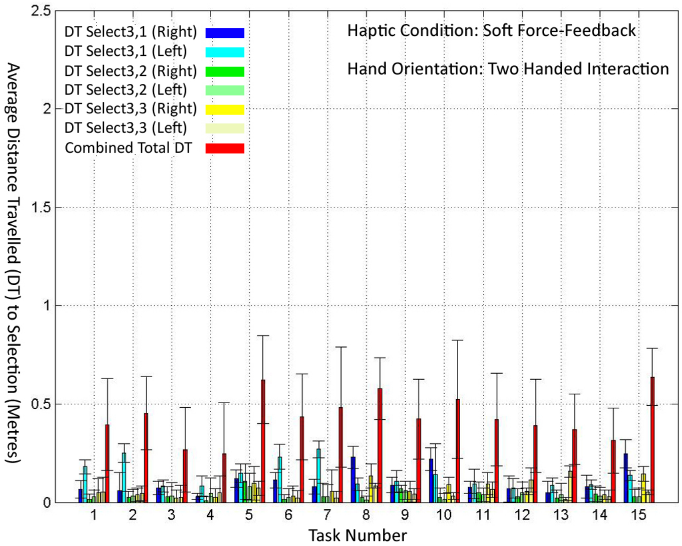


(c) NoF haptic conditions

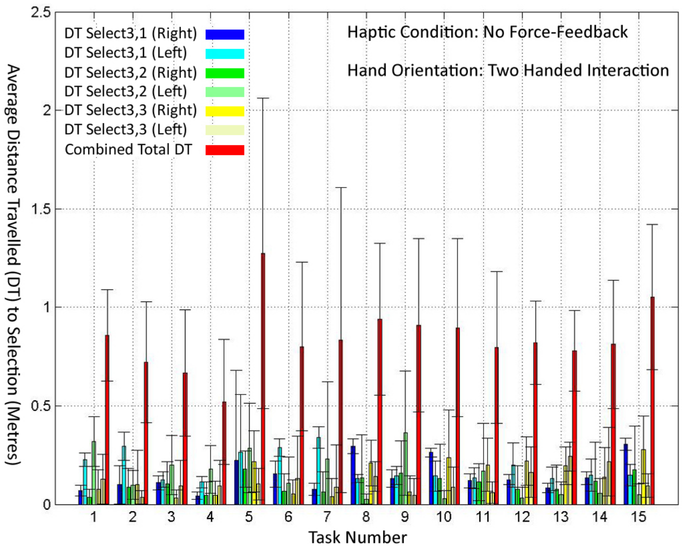
Figure 5.37: Two handed interaction (T-HI), Selection of three targets (Select3), Average MT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

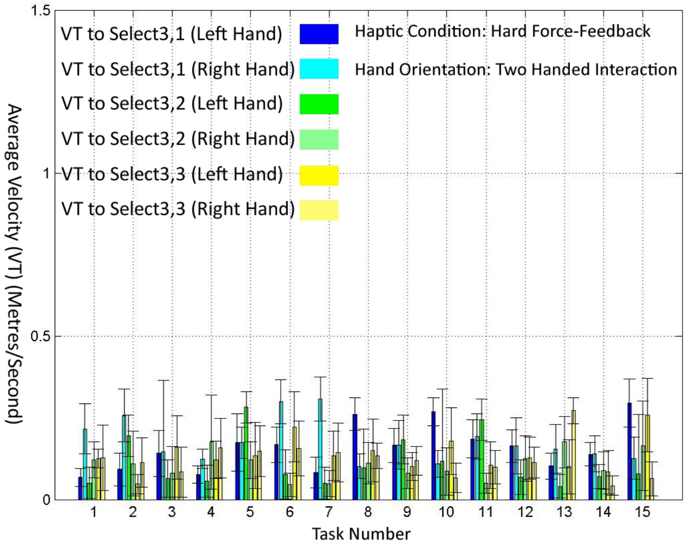


(b) Soft haptic conditions

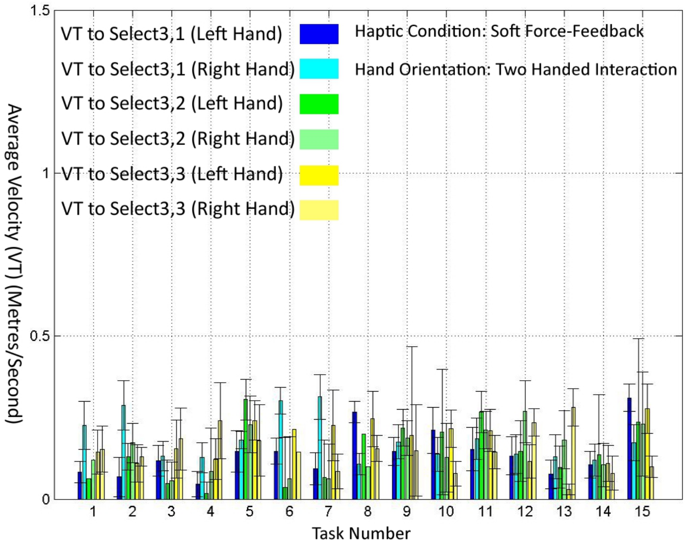


(c) NoF haptic conditions

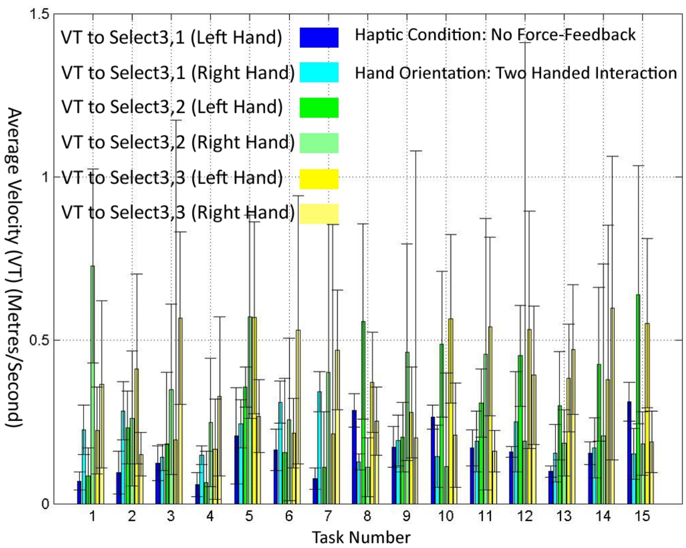
Figure 5.38: Two handed interaction (T-HI), Selection of three targets (Select3), Average DT under hard, soft and NoF haptic conditions



(a) Hard haptic conditions

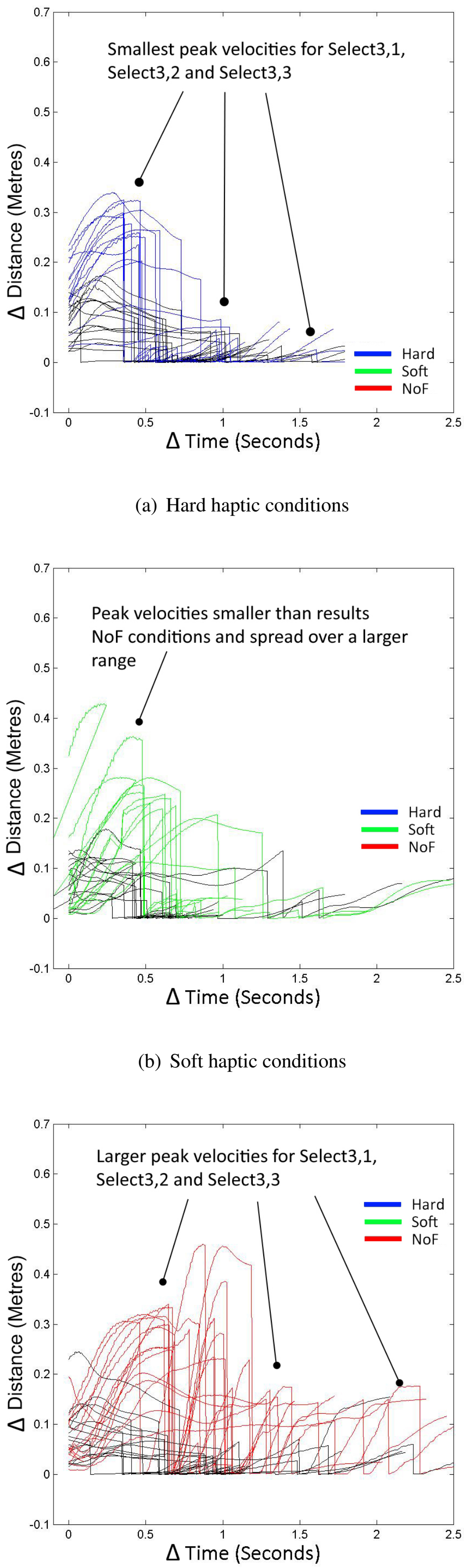


(b) Soft haptic conditions



(c) NoF haptic conditions

Figure 5.39: Two handed interaction (T-HI), Selection of three targets (Select3), Average VT under hard, soft and NoF haptic conditions

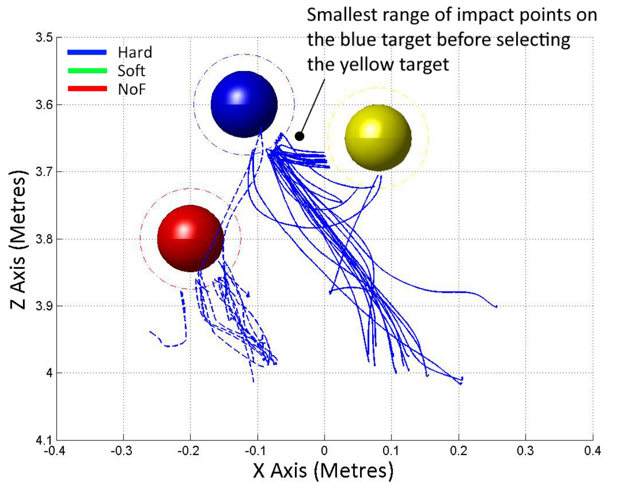


(a) Hard haptic conditions

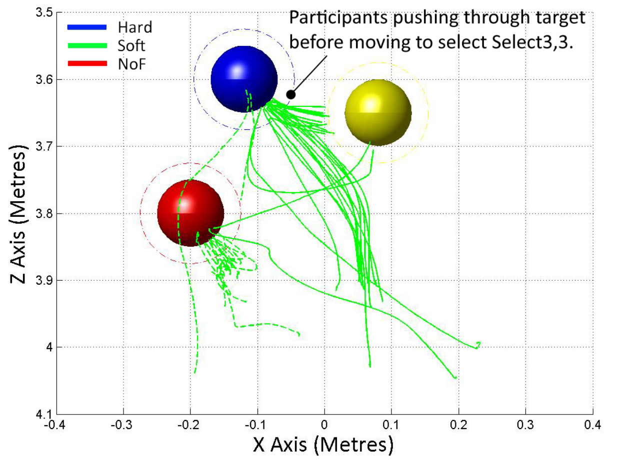
(b) Soft haptic conditions

(c) NoF haptic conditions

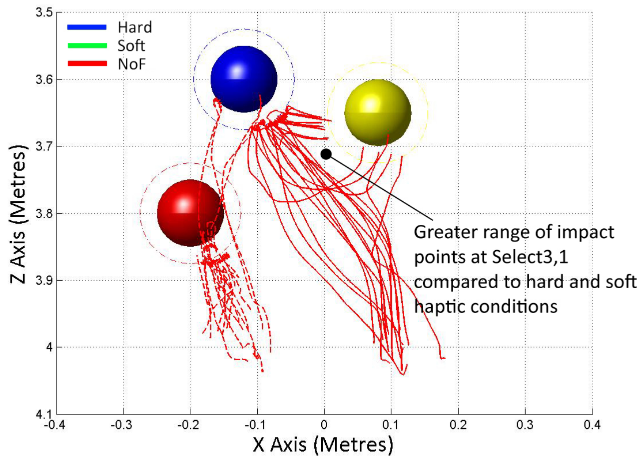
Figure 5.40: Two handed interaction (T-HI), Selection of three targets (Select3), VT profile for task 31 under hard, soft and NoF haptic conditions (black line - movement with the left hand)



(a) Hard haptic conditions

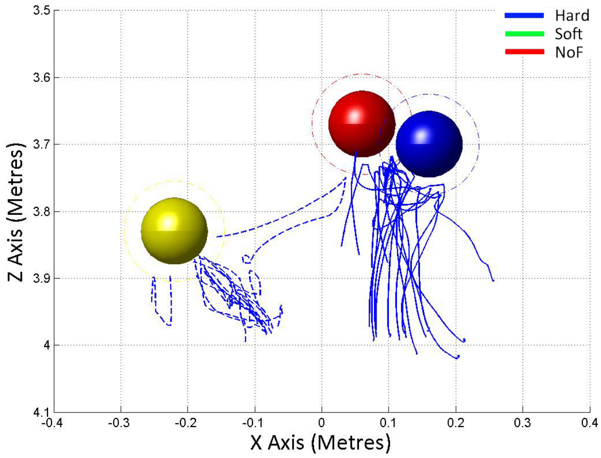


(b) Soft haptic conditions

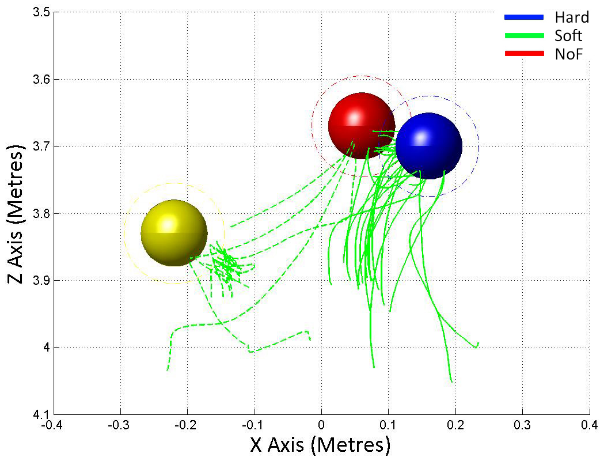


(c) NoF haptic conditions

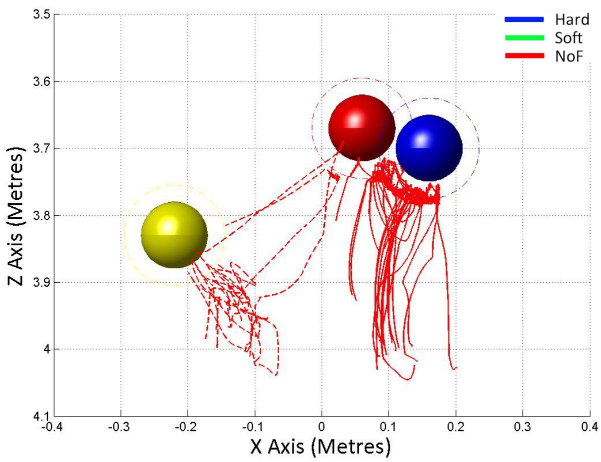
Figure 5.41: Two handed interaction (T-HI), Selection of three targets (Select3), Trajectory ZX profile for task 32 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)



(a) Hard haptic conditions



(b) Soft haptic conditions



(c) NoF haptic conditions

Figure 5.42: Two handed interaction (T-HI), Selection of three targets (Select3) Trajectory ZX profile for task 31 under hard, soft and NoF haptic conditions (dashed line - movement with the left hand)

margin reduced at Select3,3 to 0.159m and 0.135m. Interestingly, for comparisons between hard and soft feedback conditions, whilst selecting soft targets lead to smaller DT results for Select3,1 and Select3,2, when moving to the final target the shortest DT was achieved under hard feedback conditions. This demonstrates that haptic feedback affects the path taken between targets.

From the ANOVA results, we found that the difference in DT when selecting under soft feedback conditions were significant. From Table 5.11, for Select3,All the number of tasks recording p values less than 0.05 under soft feedback conditions compared to selection with hard and no responses was 15 tasks and 15 tasks respectively. For comparisons between hard and NoF conditions we found only tasks indicating a significant difference in DT. With respect to the sub-tasks, this deviation in DT occurred at Select3,2 recording more than 12 tasks for comparisons with soft feedback conditions. From these findings, this indicated that DT performance is dependent on haptic feedback condition.

Similar to Select2, the usage of the left and right hand was balanced. From Figure 5.38, we can see that participants often used both hands individually to perform the selection task. As the trends observed were similar for hard, soft and no feedback conditions, again this result suggests handedness was dependent on the spatial arrangement of targets.

5.7.3.3 Velocity Taken (VT)

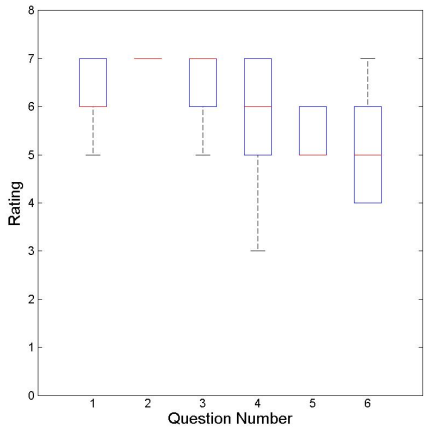
For task completion, the largest VT was NoF conditions. From Table 5.11, selecting targets with hard and soft feedback conditions was slower by 0.149m/s and 0.128m/s respectively. In contrast, the difference in VT between haptic feedback conditions was small with selection under soft feedback faster by 0.029m/s. For all comparisons between feedback conditions these observed differences were less than 1 standard deviation. Therefore, whilst selection with NoF conditions led to faster VT performances to task completion the difference was small.

With respect to the sub-tasks, selection performance for all movements was quickest under NoF conditions. From Figure 5.39, we found that VT increased between sub-tasks under NoF conditions. Conversely, VT from the first target decreased by Select3,3 under hard and soft feedback conditions. This difference between haptic feedback conditions for Select3,1 was: (Hard-NoF), -0.202m/s; (Hard-Soft), 0.012m/s; and (Soft-NoF), -0.024m/s. For Select3,2: (Hard-NoF), -0.193m/s; (Hard-Soft), -0.068m/s; and (Soft-NoF), -0.145m/s. For Select3,3: (Hard-NoF), -0.161m/s; (Hard-Soft), -0.059m/s; and (Soft-NoF), -0.216m/s. Other interesting observations included that after selecting the first target, VT when selecting with hard feedback compared to soft haptic conditions was faster for Select3,2 and Select3,3. These findings demonstrate that VT between targets was dependent on haptic feedback condition.

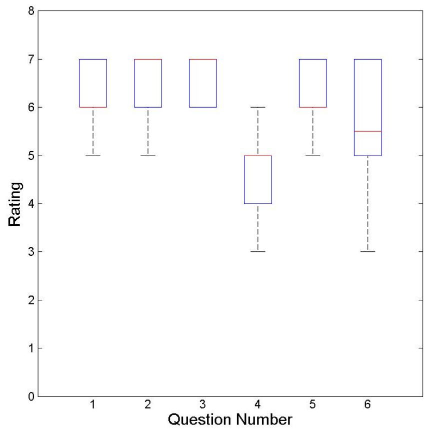
By assessing the velocity profiles we found noticeable differences in VT performances between haptic feedback condition. Shown in Figure 5.39, we found differences in the peak velocities for each feedback condition. In particular, under NoF conditions, participant were able to maintain VT between targets and achieving an overall larger VT result for task completion. When selecting targets with hard or soft force feedback, there was a drop in VT before selection of a target resulting in lower VT results.

Table 5.12: Two Handed Interaction (T-HI)- Summary of significant results between haptic conditions ('x' indicates conditions with significant differences between haptic conditions)

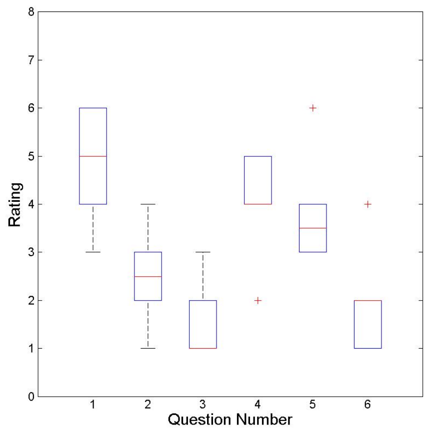
	Select1	Sel2,1	Sel2,2	Sel,2A	Sel3,1	Sel3,2	Sel3,3	Sel3,A
	MT							
Hard vs NoF								
Hard vs Soft								
Soft vs NoF								
	DT							
Hard vs NoF			x	x		x	x	
Hard vs Soft		x				x	x	x
Soft vs NoF		x	x	x	x	x	x	x



(a) Hard force feedback responses



(b) Soft force feedback responses



(c) No force feedback responses

Figure 5.43: Two handed interaction (T-HI), Usability results between haptic conditions: Questions 1) Was the interaction technique easy to use? (1=Hard to use, 7=Easy to use) 2) Did the interaction feel natural? (1=Not natural, 7=Natural) 3) Was the interaction responsive? (1=Not responsive, 7=Responsive) 4) Did you feel sick? (1=Sick, 7=Normal) 5) During the experiment were you aware of the surroundings outside of the CAVE? (1=Not aware of the outside environment) (7=Very aware of the outside environment) 6) How would you rate the interaction technique? (1=Bad, 7=Good)

5.7.3.4 Trajectory Analysis

Similar to Select2, we observed that participants used both their left and right hand and implement a strategy that best suited the selection task. As we can see in Figures 5.22 and 5.21, often the targets where segmented into areas best suited for the left and right hand selection. By doing so, participants reduced the selection class to a diffculty type to that observed for Select1 and Select2. Furthermore, this also reduced the surface effects on the target between haptic conditions.

5.7.4 Qualitative Data Analysis

From the qualitative data recorded as shown in Figure 5.43, we can see participants found all force feedback conditions easy to use and experienced little sickness. In terms of responsiveness and naturalism of interaction, conditions with haptic force feedback produced best results. Similar to selection with the right hand only, hard haptic conditions achieved the best results to task completion. In contrast, participants found conditions with no feedback not natural or unresponsive to use. Unlike selection with the right hand only, for all haptic conditions participants were aware of their outside surroundings, suggesting less presence was felt. This may be due to the hardware constraints preventing participants to fully use both hands in cooperation similar to the real world.

With respect to comparisons between bi-manual and selecting targets with the right hand only, we did not observe much difference in usability. In general, responsiveness and naturalism of interaction were better. However, the differences between the two data sets were not large.

5.7.5 Discussion

As summarised in Table 5.12, the differences in performance between haptic conditions were similar to those observed when selecting targets with the right hand only. However, when selecting multiple targets participants were able to reduce the difficulty of the presented task by pre-planning their movement for each hand. Reflected in the MT, DT and VT results, this had the net effect of turning a Select3 task into a combination of Select2 and Select1 tasks. To describe these relationships we give the following profiles:

Soft haptic condition:

Table 5.13: Two handed interaction (T-HI), Summary of results, Soft haptic condition

Performance Marker	Result
MT	- For Select1, Select2 and Select3 we found no difference in MT performance between each of the evaluated haptic force feedback conditions.
DT	- Soft haptic conditions achieved the best DT performance results for Select3.
VT	- For Select3, VT performances were better for soft haptic conditions compared to selection with hard force feedback. - Slower VT results against NoF conditions for Select1 and Select2.
Handedness	- Mixture of using the left and right hand participants planned their intended movement depending on the spatial orientation of the targets, segmenting the space between using the left and right hand. By doing so, this reduced the difficulty of the task to a set of Select1 and Select2 style interactions.

Hard haptic condition:

Table 5.14: Two handed interaction (T-HI), Summary of results, Hard haptic condition

Performance Marker	Result
MT	- MT behaviour was similar to soft and no feedback results for all selection tasks.
DT	- Best DT performance for Select1 and Select2 compared to NoF and soft haptic conditions. Worst DT results for Select3.
VT	- Worst VT results for all selection tasks compared to no and soft force feedback conditions.
Handedness	- Strategies for the left and right hands were similar to those used under soft and NoF conditions.

NoF haptic condition:

Table 5.15: Two handed interaction (T-HI), Summary of results, NoF haptic condition

Performance Marker	Result
MT	- For Select2 and Select3, MT results similar to hard and soft force feedback conditions.
DT	- Largest DT results for Select2 and Select3 compared to selection with soft and hard feedback
VT	- Best VT performances between haptic conditions for all selection tasks.
Handedness	Participants used similar hand combinations to the other evaluated haptic conditions.

The collected results demonstrate how haptic feedback and hand interaction affected selection performance and in turn the strategies used to task completion. To explain these variations, we argue that participants changed how they move their hands depending on the type of force feedback condition displayed and the spatial arrangement of targets. By looking at the trajectory graphs, we found that under no force feedback conditions, participants spent more time of the surface of targets before moving to complete the task. For Select3, this behaviour resulted in slower completion times and larger distances covered by each hand. In contrast, under soft force feedback conditions, this behaviour did not exist whereby participants, once in contact with the intended target, moved away quickly to complete the task.

With respect to bi-manual interaction, for the majority of tasks we found there was little different in performance between haptic conditions. Interestingly, by looking at the handedness of the interactions, for all three haptic conditions the recorded behaviour was similar suggesting that participants plan hand combinations best suited to the spatial arrangement of the targets. For example, the difficulty of Select2 was reduced to a set of two single selection tasks and as a result limited the surface effects as observed when only using the right hand. Nevertheless, when progressing to three targets we started to observe differences between haptic conditions.

With respect to the qualitative data, we noticed participants found moving to touch targets with soft and hard responses easier to select. In contrast, selection with no feedback achieved the worst results. This suggests that participants preferred experiencing either soft or hard feedback responses because it gave a more tangible response similar to touching a real object. Therefore, we suggest that the trade-off of supporting physical properties versus providing faster movements deserves more attention, especially in the situation for non-simple selection tasks.

To summarise, we found:

- Differences between haptic conditions similar to that observed using the right hand only
- When selecting multiple targets, participants would pre-plan their movements to reduce the difficulty of the task. As the result, the differences in performance between haptic conditions were smaller.

5.8 Summary

In this chapter we discussed the different selection strategies taken when using a natural selection technique. In particular, we highlighted the different movement patterns taken when asked to select multiple targets and how this was affected by the type of haptic force feedback experienced upon contact. More specifically, in section 5.6 we described these changes with respect to MT, DT and VT, in addition to the impact points and behaviour on the surface of targets when manoeuvring either hand to complete tasks. For Select1, we found no difference between haptic feedback conditions. In contrast, when selecting multiple targets selection with hard and soft feedback improved DT performance in particular the task efficiency when selecting target surfaces to move between objects, thus improving overall performance. VT performance was best under NoF conditions as participants were able to retain their velocity and not stop upon selection with a target. As discussed in section 5.6.5, this is an interesting result suggesting a trade-off in task efficiency and selection with multiple targets depending on haptic feedback condition.

With respect to selection using bi-manual interaction, in section 5.7 we found that this reduced the difficulty of the task. As participants were able to use both hands in cooperation, this reduced the complexity of the task. For example, Select3 was reduced to movements similar to either selecting one target with the right hand and two targets with the left hand. Similar to selection with the right hand only, haptic feedback improved performance for Select3. For Select1 and Select2, we found no difference in performance between haptic feedback conditions.

To expand upon these results, in chapter 6 we evaluated these variables further to include the effects of target size. We also assessed these results to established 3D selection models such as Fitts' law.

Chapter 6

Effect of Target Size and Haptic Force Feedback on Natural 3D Selection

6.1 Overview

In this chapter we evaluated the interaction between target size and haptic force feedback, and how this affected 3D selection performance when using a natural interaction technique. Extending results from chapter 5, we used the same 3D selection technique previously implemented and made small changes to the experimental framework. In particular, we instructed participants to perform a series of selection tasks with a single and multiple targets that also varied in size. By displaying different types of haptic force feedback felt upon selection, we identified the extent to which these conditions changed the selection strategies used to task completion with respect to the number of targets and their size. We also evaluated these results with respect to Fitts' law, identifying limitations to the state of the art in terms of modelling 3D selection. With these findings, we demonstrate the trade-off in task efficiency between haptic feedback and natural 3D selection performance.

- *Factors affecting 3D Selection (section 6.2)*- We highlight the different factors that affect 3D selection performance. We also discuss the state of the art with respect to 2D and 3D selection models and their limitations.

- *Experimental Aims and Expectations (section 6.3)*

- *Design of Experimental Framework (section 6.4)*- Description of the IVE experiment used to evaluate user performance.

- *Results- Selection of a Single Target (section 6.6)*- Selection performance between haptic feedback conditions and target size when moving to acquire a single target.

- *Results- Selection to Two Targets (section 6.7)*- Selection performance between haptic feedback conditions and target size when moving to select two targets.

6.2 Factors affecting 3D Selection

Within HCI, the study of 2D and 3D selection performance is well founded. Work by Ware, Grossman and Murata, explored the difficulties associated with task acquisition by attempting to outline the factors that describe the underlying user performance [GKB07] [MI01] [AW00a]. Through this work, validated interaction models exist, such as Fitts' law that describes how targets with a smaller fixed size require more time to select [Fit54]. However, as discussed by Mackenzie and Buxton a common limitation of these studies was to keep target size constant [MW92]. In general, the interaction of these factors on 3D selection, in addition to others such as haptic force feedback still remains unclear.

Discussed in sections 2.5 and 5.3, a common trend when developing new 3D selection models is to provide extensions to Fitts' law. To explore this research area in more detail, another direction to consider is the relationship between lower-level motor control theory and user performance [Fit54]. As discussed by Mcguffin and Balakrishnan, examination of kinematic data for individual target acquisitions reveals that the movement of the user is often not a single/smooth motion, but rather composed of a sequence of one or more sub-movements [MB05]. In particular they show that the first sub-movement is typically large and fast, covering most of the distance to the target; followed by subsequent, smaller and slower movements, correcting for any undershoot or overshoot of the initial movement. These findings demonstrate the underlying complexities with respect to 3D selection. Therefore, we believe when investigating factors affecting selection behaviour it is important to consider the ballistic movements thoroughly.

To date, the simplest model explaining the effects of target size is the deterministic iterative-corrections model [MAK+88]. This suggests that the sub-movements performed during pointing tasks each have: equal duration, travel a constant fraction of the remaining distance to the target, and are all executed under closed-loop feedback control such as visual or kinaesthetic feedback [CG83] [Kee68]. Alternatively, another set of theories define a set of phases whereby selection is described by an initial, open-loop ballistic impulse, followed by a corrective, closed-loop, 'current control' phase [Woo99] [MAK+88]. A common theme for these models is that the latter corrective sub-movements are performed under closed-loop control. As a result, it is suggested that the extra information provided by larger targets should improve user performance.

Other models includes Cannon's a target-threshold control theory model. This was developed for predicting human-machine movement time, by allowing the parameters of Fitts' speed and accuracy law to be determined before system construction. By doing so, they extended Fitts' law for it to be used as a predictive design engineering tool for new systems as well as in its traditional role of after-the-fact analysis. The target-threshold model successfully characterised human control movement times, before system construction, in experiments involving camera pointing for a new class of point-and-direct telerobotics [Can94]. Zhai also discussed that pointing tasks in HCI obey certain speed-accuracy trade-off rules [ZKR04]. In particular, they further suggest that by operating with different speed or accuracy biases, performers may utilise more or less area than the target specifies, introducing another subjective layer of speed-accuracy trade-off relative to the task specification.

Accot and Zhai also discuss trajectory based interactions to model pointing tasks in 3D environments. They further suggest that user performance that involves 3D trajectories cannot be successfully modelled with Fitts' law. As a result, they explored the possible existence of robust regularities in trajectory-based tasks such as steering through tunnels. Through this they found that a steering law existed [AZ97]. Other studies by Zhai et al, investigated the Fitts' law parameters with respect to the information and non-information aspects of pointing [Zha04].

Another factor currently being explored is angular position of the target. In particular with co-located 3D interactions, researchers believe the positional rotation of the target relative to the body pose may affect the ballistic movement to target acquisition. Of the few studies evaluating this area, Gibbs compared several levels of angular gain (both positional and velocity) in the performance of target selection on a display, while Buck studied how angular gains on different joysticks interacted with different gains related to target widths on the display [KBSM10]. Further studies by Kondraske proposed a model of direct target acquisition that used angular measures in the index of difficulty, motivated by the use of joint angles to determine end effectors position in biomechanical modelling [Kon94]. The most relevant study by Groosman and Balakrishnan extended Fitts' law for trivariate targets by modelling human performance for selecting 3d targets in a volumetric display as a factor of the width height and depth of the target as well as the amplitude of the movement and angle of selection [GB04]. They demonstrate the effects of size and angular position proposing extension of Fitts' law which outperformed previous models. Nevertheless, similar to target size there is little consideration to the type of haptic feedback being provided and in turn the wider interaction of these factors.

6.3 Experimental Aims and Expectations

Building upon the main results from chapter 5, we believe when moving to select a single target haptic feedback will not affect selection performance regardless of size. As haptic feedback is only provided upon contact, this extra information cue will not provide any additional benefit to overall task performance. As a result, we expect that task efficiency will be based primarily upon the size of the target, whereby smaller targets will be harder to select.

However, for more complex scenarios such as selection of multiple targets, we expect to find a trade-off in task efficiency with respect to different haptic force feedback conditions and size. For example, when moving to select a large target, haptic feedback will have a detrimental effect on the task efficiency as users have to put in more effort to move around objects that provide a physical resistance. At present, we do not have any prior expectations to the trade-off between different combinations of target sizes and their selection order. The study of these factors will be characterised by changes in MT, DT and VT.

6.4 Design of Experimental Framework

6.4.1 Implementation of IVE experiment

Following a similar design to the experiment conducted in chapter 5, we created an IVE where we asked participants to perform a series of 3D selection tasks using their right hand only. Shown in Figure 6.1

we instructed participants to placed their index finger inside the thimble of the right haptic device which they then used to manoeuvre a 3D haptic contact point in reference to the natural selection technique previously implemented in section 5.5.1. By intersecting the 3D haptic contact point with the surface of an intended target, participants were able to perform selection tasks with a set of spherical targets presented in front of them. With this setup, we implemented a experiment that covered two types of the selection tasks: selection of one target ('Select1') and the selection of two targets ('Select2'). Again, similar to the study conducted in chapter 5, we evaluated three haptic force feedback conditions rendered upon collision between the 3D haptic contact point and targets: hard force feedback ('Hard'), soft force feedback ('Soft') and no force feedback ('NoF').

As shown in Figure 6.2, the experiment consisted of displaying either one or two targets for participants to select: either one white sphere target, or one white and one yellow 3D sphere target each placed on a neutral grey rod. We chose these colours due to their high contrast specific to the display devices used. Also, by placing the targets on rods connected to the ground, this helped the perception of size against distance. Again, we placed these sphere targets within an outdoors scene to infer real-world responses whilst interacting within the presented environment. By doing so, this also gave a fixed horizon level which helped reduce any adverse side effects caused by simulator sickness. Additionally, we used a dark ground colour as to give a strong contrast between the environment and the targets so that participants could easy identify which target to select first. In general and throughout the design phase, we piloted all the colours, sizes and positions of the targets to ensure that they were suitable for the experiment and comparable to earlier captured results.

When participants were placed within the IVE, we gave clear instructions to perform a set of selection tasks involving one or two of the displayed 3D sphere targets. To investigate the effect of size on selection performance, we defined through piloting two different diameter sizes of sphere targets:

1. *Small ('SelectS')* - 1cm in diameter,
2. *Large ('SelectL')* - 8cm in diameter

We placed these sphere targets in random positions all in front and within arm's reach of the participant adhering to the usable workspace of the hardware setup. To limit the length of the trial, we did not look at the interaction between individual target dimensions such as width, height and depth as done so in other studies [AZ03] [GKB07]. Therefore, we chose sphere targets displaying a uniform size from every perspective.

Through this design, we assessed two types of selections tasks:

1. *Selection of one target ('Select1')* - Only one target in the scene, one white sphere. When presented, we instructed participants to select the white sphere only. We evaluated the effects of three different sizes of targets - small (SelectS) and large (SelectL). For each of these sizes, this defined a class of selection tasks, which we used to test a set of targets placed in positions randomly generated covering different areas in front and within arm's reach. We used this set of positions for each selection task class.

Figure 6.1: Typical usage of equipment using the right hand only

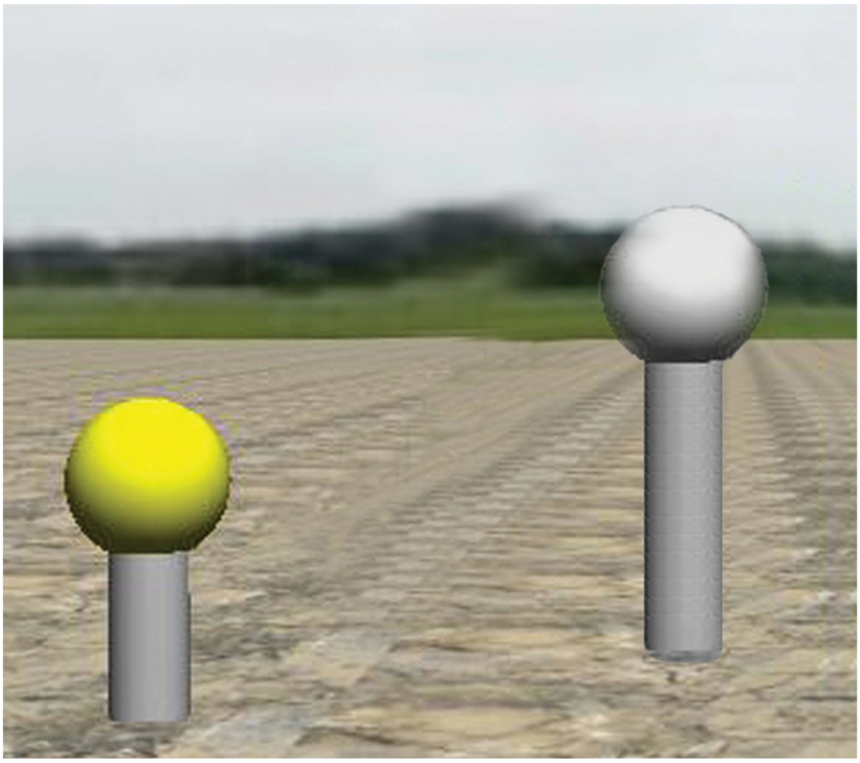


Figure 6.2: Design of IVE experiment

Table 6.1: Breakdown of individual selection tasks for each experiment trial

Haptic conditions:	Target size combinations					
	Select1		Select2			
	SelectS	SelectL	SelectSS	SelectSL	SelectLS	SelectLL
Hard	10	10	10	10	10	10
Soft	10	10	10	10	10	10
NoF	10	10	10	10	10	10

2. *Selection of two targets ('Select2')* - Only two objects in the scene - one white and one yellow sphere. Participants explicitly instructed to select the white sphere first ('Select2,1') and then the yellow target sphere ('Select2,2'). We evaluated two different sizes of targets thus resulting in 4 different combinations and in turn classes of selection tasks to assess: 'Small-to-Small' ('SelectSS'), 'Small-to-Large' ('SelectSL'), 'Large-to-Small' ('SelectLS') and 'Large-to-Large' ('SelectLL'). Similar to Select1, for each class of selection task, we placed these targets in random positions varying in distance, close and far away, all in front and within the participant's workspace.

To evaluate the effects of haptic force feedback, for each target arrangement, we tested the following three feedback conditions. Implementation details for this conditions are described in section 5.5.1:

1. *Hard Force Feedback ('Hard')*- A hard force feedback response when a target is selected, similar to touching a wooden or marble table.

2. *Soft Force Feedback ('Soft)*- A soft force feedback response when in collision with a target, similar to pressing on a cushion or sponge.

3. *No Force Feedback ('NoF')*- No force feedback cues when in contact/selecting a target. Participants hand can go through the surface of an object without any mechanical resistance.

For each the identified classes of selection tasks, we tested 10 different random sphere arrangements (totalling 20 for Select1 and 40 for Select2). Through piloting we ensured that the distribution of these tasks were all uniform and considered with respect to limiting any distracting factors [WPS+02]. For the defined 10 sphere arrangements, these covered the different distance ranges possible, close to far away from the participant, but always within their arm's reach. As shown in Table 6.1, when running the experiment, we combined both lists of selections tasks from Select1 and Select2 together, representing a total of 60 individual tasks that each participant completed.

To limit any learning effects of a certain spatial target arrangements, we displayed each of the 60 selection tasks in a random order. For every individual selection task, participants were instructed to use their right hand only to select a target. When selected, the target would turn a dark grey colour- a visual selection cue commonly used. Upon task completion, we designed a reset crosshair to appear, which we then instructed the participant to touch. As described in section 5.5.2, this consisted of three red spheres, 1.25cm in diameter positioned in a small triangle so that the 3D haptic contact point could only touch all of them in a certain position (the centre of these three spheres when positioned in a triangle). By doing so, we ensured that every participant, for each selection task, started their hand from the same position, maintaining consistency throughout all the trials run. Once selected and each task successfully completed, we displayed a new selection task automatically generated in a random order from the list of 60. We repeated this process until the participant finished all the tasks.

In total, each participant ran the experiment for only one force feedback condition. Primarily this was done so that we could use the same list of 60 selection tasks for each condition, and in turn limit any learning affects that may occur from repeated measures. Also, as each trial lasted 12 minutes on average to complete, we wanted to limit any effects cause by fatigue on subsequent conditions tested. When the participants confirmed that they were ready, we started logging the time taken and positional data of the right hand during each task.

6.5 Experiment Procedure and Participants

We collected data from 30 participants, all male. As our hand movements are heavily dependent on our physical dimensions and posture, we chose participants all with similar backgrounds, heights and age. All were right handed with active lifestyles suggesting good hand-eye coordination. They were also 5' 8" to 5' 9" in height with an age range of 20-23. The participants were taken from members of the Department of Computer Science at University College London and post-graduate students. 14 participants had previously used the ReaCToR but not the GRAB arms. A breakdown of the participant details is given in Table 4 (see Appendix C).

Before starting the experiment we gave each a demonstration of the equipment and thorough instructions. Each participant had 10-15 minutes to accustom themselves with the GRAB haptic interface, ReaCToR, head tracking and the implemented 3D interaction technique to level out any learning effects. Once done, we repeated the instructions, answered any questions, and asked if they were ready to continue with the experiment. As the length of the experiment was short we gave no financial compensation for their help. Also, we did not record any qualitative data besides the ease of use rating for the interaction technique asked at the end of the experiment, which averaged at 6.3/7.

To recap, as each participant performed their set of selections tasks for one force feedback condition only (in total 10 subjects for each feedback condition tested), therefore we present the results as a in between subjects comparison of the target size combinations, separated by haptic feedback condition. Similar to experiments in chapters 4 and 5, at the start of each trial we included 15 selection tasks that we discounted in the results, as to eliminate the learning effects on the data of the participants at the start the experiment. When participants made false movements, defined as selecting targets in the wrong order, this was logged by the implemented data capture system and excluded from the results. All other movements were included in the study.

6.6 Results- Selection of a Single Target (Select1)

For a full list of trajectory and velocity graphs (see Apprendix C and attached CD under directory label 'Appendix C').

6.6.1 Selection of a Small Sized Target (SelectS)

6.6.1.1 Movement Time (MT)

MT performance between haptic force feedback conditions:
When selecting a single small target, participants completed the task with least MT under hard feedback conditions. Depicted in Figure 6.3, the computed average MT under hard force feedback conditions was 0.832 seconds. In comparison, from Table 6.2, MT performance under soft and no feedback conditions was slower by 0.011 seconds and 0.067 seconds respectively. With respect to MT performance between soft and no feedback conditions, selecting targets that provide soft feedback responses was on average faster by 0.056 seconds. By evaluating results in Table 6.2, these observed differences in MT between haptic conditions were within 1 standard deviation. As a result, this suggests that the effect of haptic feedback on MT performance was small.

By computing a set of ANOVA results, we analysed the significance of the observed differences in MT performance. Shown in Table 6.2, we found only a few tasks wherein the difference in MT for all comparisons between haptic feedback conditions resulted in p values less than 0.05. For differences between using both hard and soft feedback conditions against to selection with no responses resulted in only 3 out of 10 tasks with significantly better MT performances. With respect to MT comparisons between selection with hard and soft feedback responses we found no tasks. This indicates that selection with or without haptic force feedback has little or no affect on MT performance for SelectS.

MT performance for target sizes SelectS against SelectL:
On average participants took the largest MT when selecting a small sized target. In Table 6.3, MT performance for SelectL was faster by: 0.191 seconds under hard conditions, 0.227 seconds under soft feedback conditions, and 0.346 seconds under NoF conditions respectively. With respect to results in Table 6.3, these observed differences in MT were within 1 standard deviation. Therefore, this suggests that the single selection of a small target resulted in slower MT results than SelectL.

From the computed ANOVA results, results achieved for SelectS were significantly different to those captured when selecting large targets. Shown in Table 6.3, we found at least 8 tasks MT for SelectS that were slower compared to selection large targets for all haptic conditions whereby p values were less than 0.05. This shows that small targets increases MT when selecting a single target for each haptic condition.

MT performance against index of difficulty:
To assess MT performance across all the selection tasks, we plotted the average MT against each task's index of difficult (ID). We computed the individual IDs as defined in section 3.4.3, and fitted a linear polynomial using a least squares estimate. Shown in Figure 6.6(a), we found the MT behaviour observed under soft and hard feedback conditions were similar for all IDs. With respect to selection with NoF conditions, participants took more MT to task completion with tasks with higher IDs. Altogether, the disparity in MT performance between all haptic conditions was small.

By computing the residuals for each of the linear estimations, we evaluated how well the ID values obtained using a Fitts' law model fitted to the captured MT data. The R^2 values for SelectS under hard, soft and no force feedback conditions were 82%, 63% and 38% respectively. This suggests that selection under hard feedback compared well to a Fitts' law model. In contrast, selection without haptic feedback did not. This is an interesting result, indicating that the 3D movement behaviour without haptic feedback led to a selection strategy that may not be compatible with Fitts' law.

6.6.1.2 Distance Travelled (DT)

DT performance between haptic force feedback conditions:

Participants selected a small target with the least DT when using hard feedback conditions. Depicted in Figure 6.4, the average DT to select a single target providing hard responses was 0.458m. From Table 6.2, comparatively selection under soft and no feedback conditions lead to larger DT results by 0.020m and 0.065m respectively. With respect to Table 6.2, differences in DT between hard and no feedback conditions were greater than 1 standard deviation. In contrast, results between hard and soft feedback conditions, and soft against no feedback conditions were both less than 1 standard deviation. This suggests that only hard feedback responses improved DT performance when selecting a small target.

From the set of ANOVA results, we found that the DT for each haptic feedback condition significantly different. Shown in Table 6.2, comparisons between hard and soft feedback conditions to selection with no response led to 7 tasks with p values less than 0.05. Interestingly, we also observed 8 tasks whereby selection with soft targets resulted in significantly larger DT to task completion to hard haptic conditions. This demonstrates that different haptic conditions affected the DT when selecting a small target, whereby hard feedback responses led to the shortest paths to task completion.

DT performance for target sizes SelectS against SelectL:

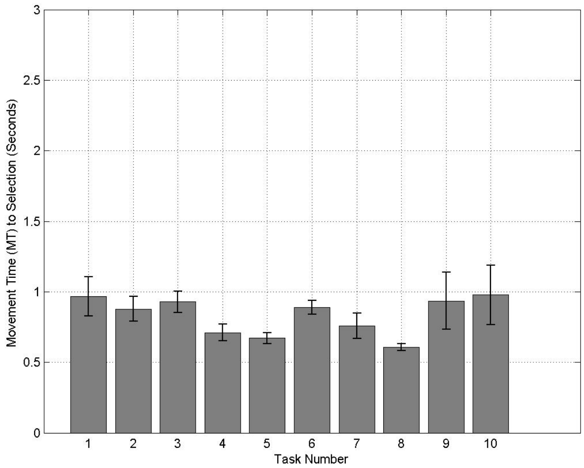
Participants selected a small target with the greatest DT. From Table 6.3, selection for SelectL achieved less DT by: 0.085m under hard feedback conditions, 0.095m under soft feedback conditions, and 0.124m under NoF conditions respectively. By evaluating Table 6.3, these differences were within 1 standard deviation. This demonstrates that whilst SelectS lead to larger DT results to task completion, the variation to large target sizes were small.

To analyse this trend, we computed a set of ANOVA results. Summarised in Table 6.3, we found 9 tasks where the DT performance for SelectS against SelectL led to p values less than 0.05. This result was also evident for each haptic condition assessed. Therefore, this indicates that selection of a single small target increased DT performance to task completion.

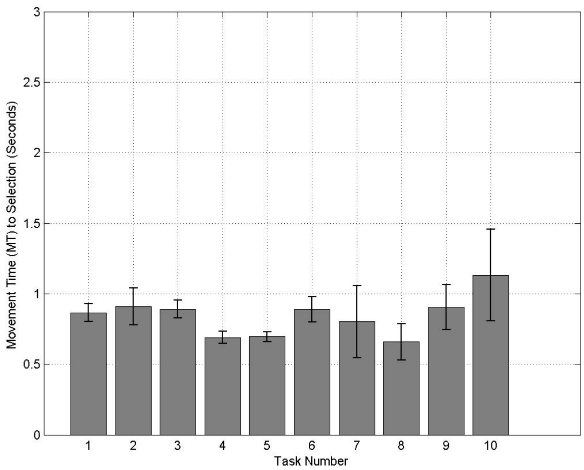
6.6.1.3 Velocity Taken (VT)

VT performance between haptic force feedback conditions:

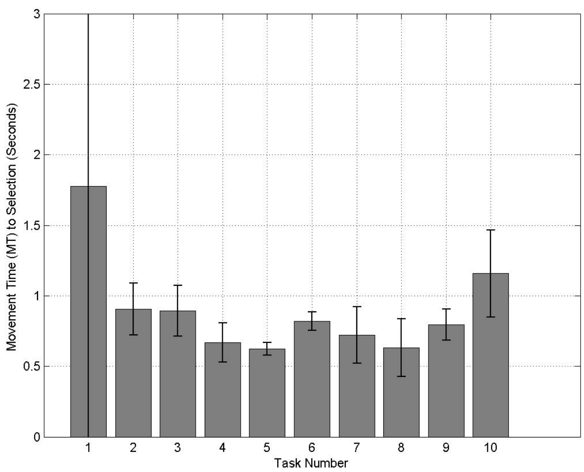
Participants completed the task with the largest velocity under NoF conditions. On average VT performance to task completion was 0.639m/s when selecting targets that provided no feedback. Shown in Table 6.2, when using hard and soft feedback conditions this led to slower results by 0.089 m/s and 0.073 m/s respectively. For differences in VT between using hard and soft feedback conditions, participants



(a) Hard haptic condition

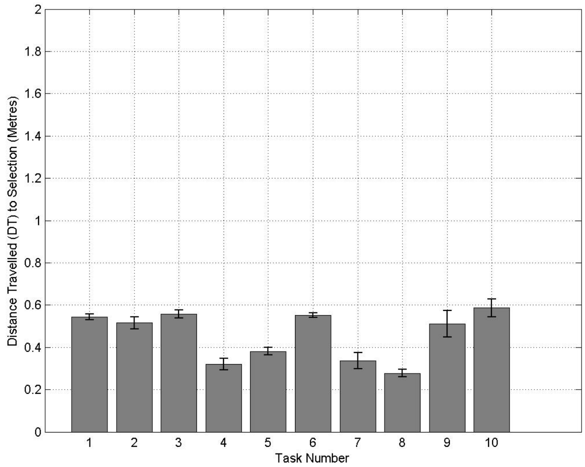


(b) Soft haptic condition

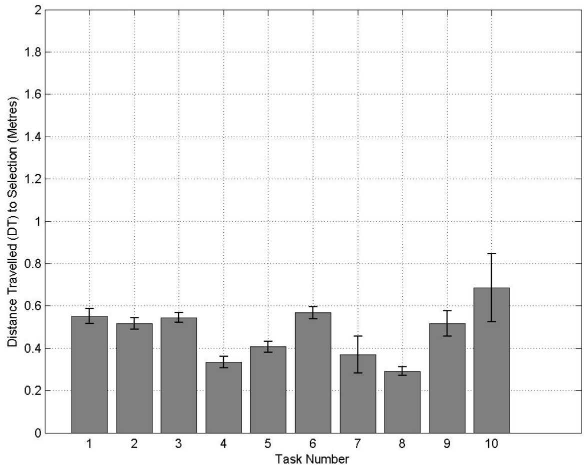


(c) NoF haptic condition

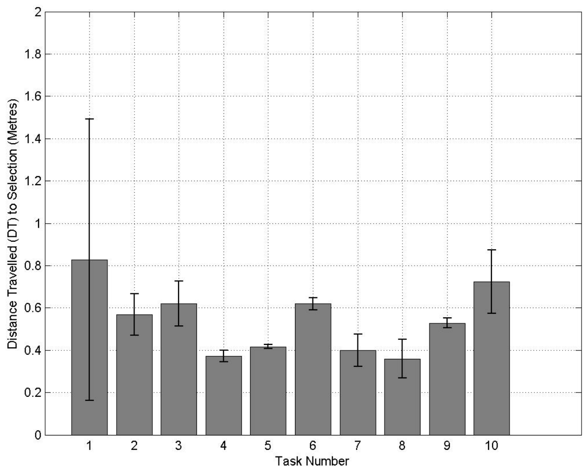
Figure 6.3: Selection of a small target (SelectS), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

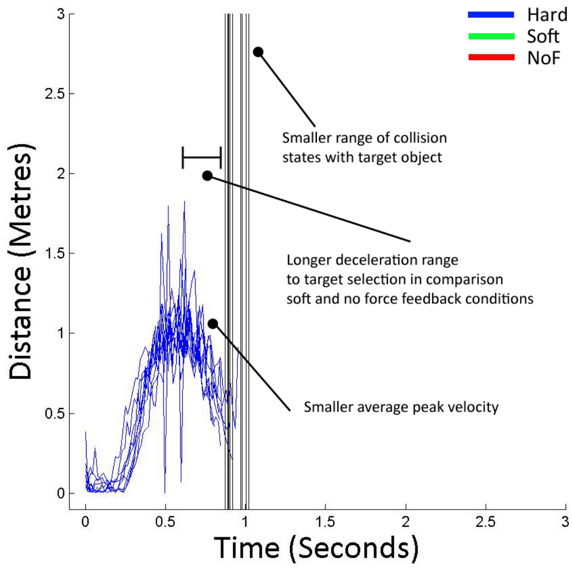


(b) Soft haptic condition

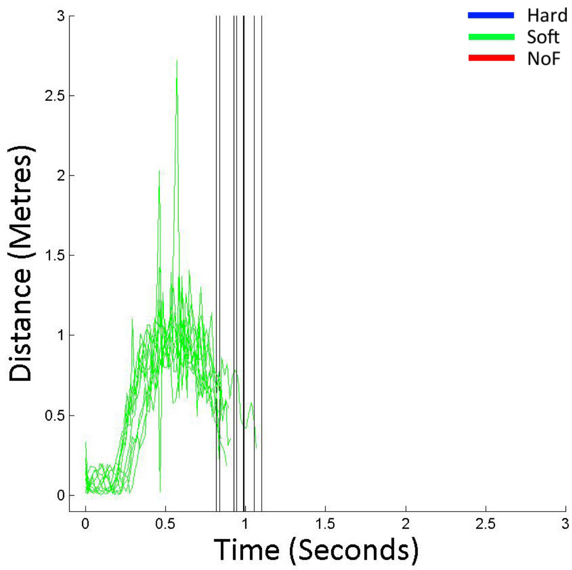


(c) NoF haptic condition

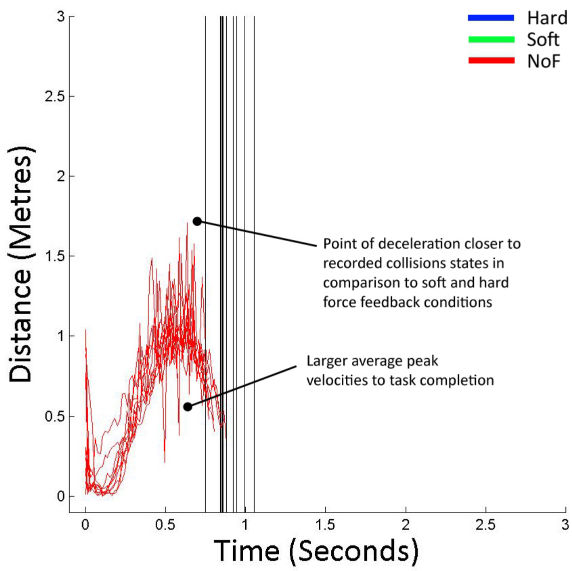
Figure 6.4: Selection of a small target (SelectS), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

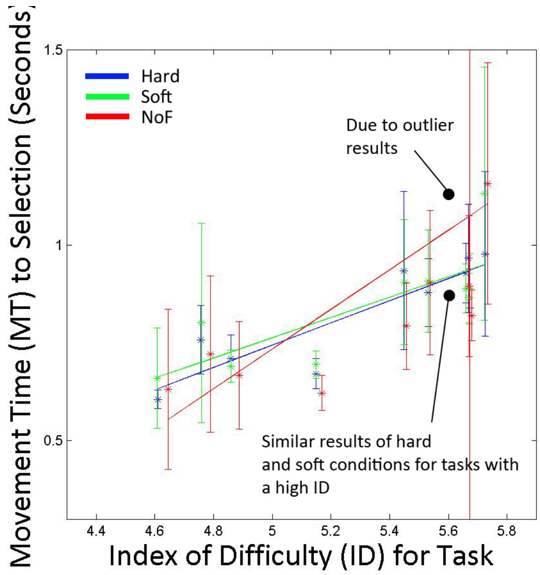


(b) Soft haptic condition

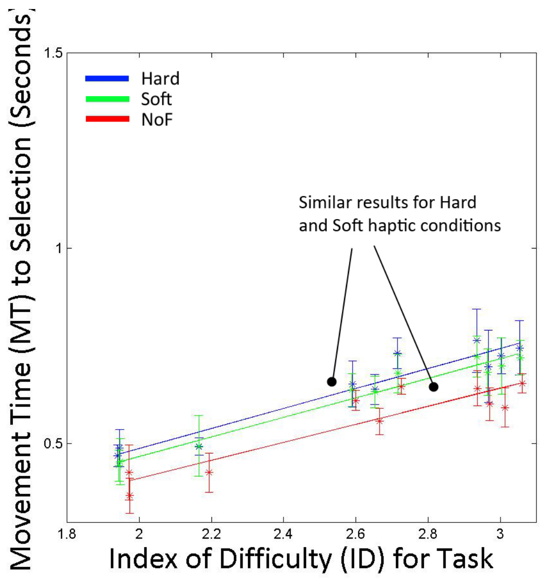


(c) NoF haptic condition

Figure 6.5: Selection of a small target (SelectS), Velocity profile for task number 96

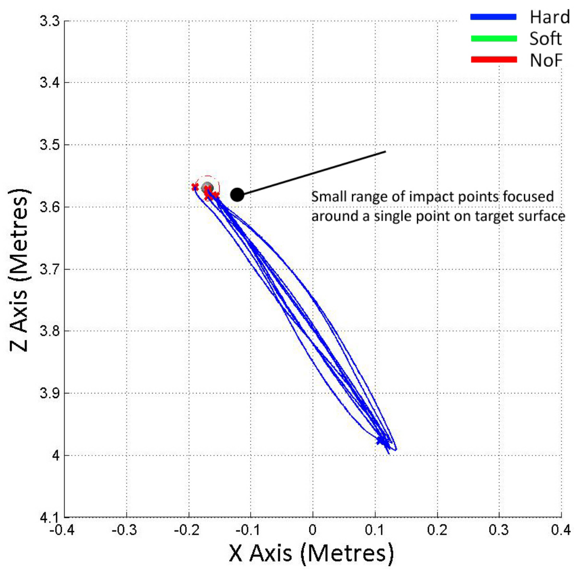


(a) SelectS

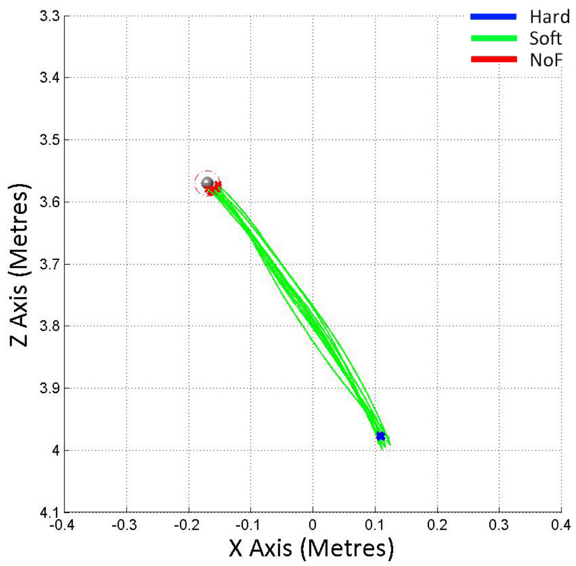


(b) SelectL

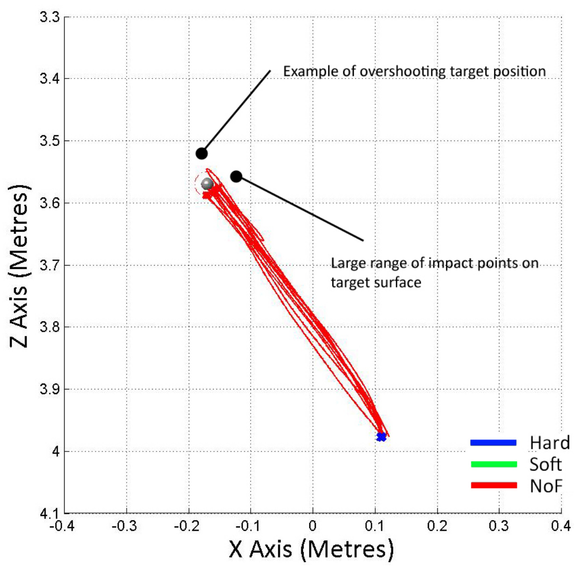
Figure 6.6: Selection of one target (Select1), MT against ID for each haptic condition



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.7: Selection of a small target (SelectS), Trajectory profile for task number 91

Table 6.2: Select1, Average difference, standard deviation and ANOVA results for MT, DT and VT between haptic conditions (n=10 for each haptic condition, and highlighted text indicates significiant results)

	Average Difference in:					
	MT		DT		VT	
Haptic condition:	SelectS	SelectL	SelectS	SelectL	SelectS	SelectL
(Hard - NoF)	-0.067	0.088	-0.085	-0.046	-0.089	-0.181
(Hard - Soft)	-0.011	0.024	-0.020	-0.010	-0.017	-0.036
(Soft - NoF)	-0.056	0.064	-0.065	-0.036	-0.073	-0.145
	Standard Deviation of Difference in:					
(Hard - NoF)	0.274	0.027	0.076	0.018	0.042	0.053
(Hard - Soft)	0.068	0.016	0.031	0.014	0.023	0.023
(Soft - NoF)	0.304	0.027	0.077	0.020	0.050	0.046
	ANOVA Results- Number of Tasks with p< 0.05					
Hard vs NoF	3	9	8	9	6	7
Hard vs Soft	0	6	8	9	5	8
Soft vs NoF	3	8	7	8	6	7

Table 6.3: Select1, Average difference, standard deviation and ANOVA results for MT, DT and VT between target size combinations (n=10 for each haptic condition, and highlighted text indicates significiant results)

	Average Difference in:								
	MT			DT			VT		
Size condition:	Hard	Soft	NoF	Hard	Soft	NoF	Hard	Soft	NoF
(SelectS-SelectL)	0.191	0.227	0.346	0.085	0.095	0.124	-0.021	-0.040	-0.112
	Standard Deviation of Difference in:								
(SelectS-SelectL)	0.226	0.227	0.439	0.211	0.220	0.255	0.145	0.150	0.093
	ANOVA Results- Number of tasks where difference between target sizes led to p< 0.05								
(SelectS-SelectL)	8	8	9	9	9	9	8	7	8

selected soft targets faster by 0.017 m/s. From Table 6.2, selection performance comparing both hard and soft haptic feedback conditions to selection with no responses was greater than 1 standard deviation. For differences in VT between hard and soft feedback conditions this was less than 1 standard deviation. Therefore, these results show that VT performance was best when selecting targets that provided no force feedback.

By computing a set of ANOVA results, we evaluated the extent of the observed differences in VT between haptic feedback conditions. Shown in Table 6.2, for results achieved in both hard and soft conditions, we recorded 6 tasks where there was a significant difference in VT performance against results achieved selecting targets with no feedback responses. Interestingly, we also recorded 5 tasks for comparisons between hard and soft haptic conditions indicating a significant difference in VT performance. This indicates that the type of haptic felt upon selection affected VT performance for SelectS.

To analyse the VT behaviour over the ballistic movement to selection, we plotted a series of velocity profiles for each task and haptic condition (for a database of velocity profiles see appendix C). In Figure 6.5, we found that the peak velocities achieved when selecting targets providing no and soft force feedback were higher compared to using hard feedback conditions. Participants also carried more velocity just before contact with targets that exert no feedback in contrast to selection with hard or soft targets. In essence, the deceleration observed before selecting the target with no force feedback was smaller leading to higher VT results to task completion.

VT performance for target sizes SelectS against SelectL:
VT performance when selecting a small target was slower compared to results achieved acquiring both hard and medium sized targets. Shown in Table 6.3, compared to SelectL, VT for SelectS was slower by: 0.021m/s under hard feedback conditions, 0.040 m/s under soft feedback conditions, and 0.112 m/s under no feedback conditions. Interestingly, the biggest disparity between target sizes occurred for NoF conditions suggesting an interaction between haptic feedback and target size on VT performance.

From the computed ANOVA results, the difference in VT for SelectS compared to SelectL was significant. Summarised in Table 6.3, we found at least 8 tasks wherein the difference in VT achieved in SelectS was significantly slower to SelectL. Furthermore, this trend was also evident for all three haptic feedback conditions. This indicates that a small target size affected VT performance for each haptic condition.

6.6.1.4 Trajectory Analysis

We found slight variations when selecting a small target between hard, soft and NoF haptic conditions. Shown in Figure 6.7, whilst the trajectories to the target were similar between all haptic conditions, we observed differences in selection behaviour upon the surface of the target. Specifically, under hard and soft feedback conditions, participants selected the target with a smaller distribution of impact points compared to selection with no feedback conditions. Furthermore, under hard and soft feedback conditions there were less instances of overshooting and moving beyond the target as evident under no feedback conditions. This may explain the extra DT observed when selecting targets under NoF haptic conditions.

6.6.2 Selection of a Large Sized Target (SelectL)

6.6.2.1 Movement Time (MT)

MT performance between haptic force feedback conditions:

For SelectL, MT performance was quickest under NoF conditions. Depicted in Figure 6.8, the computed average MT when selecting a target that provided no responses was 0.553 seconds. From Table 6.2, MT when selecting targets exerting either hard and soft feedback compared to NoF conditions was faster by 0.088 seconds and 0.064 seconds respectively. With respect to differences between hard and soft feedback conditions, MT was 0.024 seconds faster when selecting soft targets. By evaluating Table 6.2, these differences in MT between selection with and without haptic feedback was greater than 3 standard deviations. For MT differences between hard and soft feedback conditions this was greater than 1 standard deviation. Therefore, these results demonstrate the changes in MT behaviour when selecting a large target depending on haptic feedback responses, where best performances were achieved under NoF conditions.

From the computed ANOVA results, this further highlighted the interaction between haptic feedback and MT. Shown in Table 6.2, the number of tasks under soft and hard conditions compared to selection without haptic feedback that achieved p values less than 0.05 was 8 and 9 respectively. We also found 6 tasks whereby selection using soft targets achieved significantly faster MT than using hard feedback conditions. This indicates that hard and soft haptic conditions had a detrimental effect on MT performance when selecting a large target.

MT performance for target sizes SelectL against SelectS:

Participants selected large targets with the least MT in contrast to SelectS. Shown in Table 6.3, SelectL achieved better MT than SelectS by: 0.191 seconds using hard feedback conditions, 0.227 seconds using soft feedback conditions, and 0.346 seconds using no feedback conditions. From Table 6.3, these differences were less than 1 standard deviation, and evident for all haptic conditions. Therefore, these results indicate a small benefit to MT performance when selecting a large single target.

By computing a set of ANOVA results, we found that these differences in size when selecting a large target resulted in significantly better performances. Shown in Table 6.3, we found that on average SelectL resulted in significantly better MT values in more that 8 out of 10 tasks to selection against SelectS. This trend was also evident for each haptic condition. This confirms the trend that selecting large targets improves MT performance.

MT performance against index of difficulty:

By plotting MT against ID, we evaluated the performance across all tasks. In Figure 6.6(b), we found that MT performance for all IDs was quickest when using NoF conditions. In contrast, selection with targets exerting hard and soft feedback achieved larger MT results. These results demonstrate the difference in MT behaviour between hard, soft and no feedback conditions whereby selection with either hard and soft feedback was detrimental to performance.

Interestingly, from the computed residual values, selection with hard and soft feedback conditions achieved the best fits. Selection with hard and soft force feedback conditions resulted in a 92% and 96% fit to the variance of captured MT respectively. For selection with no feedback conditions R^2 was lower at 84%. Similar to SelectS, results with haptic feedback achieved best fits in contrast to selection with no force feedback. Furthermore, the estimates for SelectL were better than those computed for SelectS. This suggests a limitation in the Fitts' law model when targeting small objects.

6.6.2.2 Distance Travelled (DT)

DT performance between haptic force feedback conditions:

Participants selected a large target with the least DT using hard feedback conditions. Shown in Figure 6.9, the computed average DT to task completion using hard feedback conditions was 0.373m. From Table 6.2, DT under soft and NoF conditions compared to selection with hard feedback was greater by 0.010m and 0.036m respectively. By evaluating results in Table 6.2, differences in DT between both hard and soft feedback results to selection with no feedback were greater than 1 standard deviation. In contrast, differences between DT results achieved under hard and soft conditions were less than 1 standard deviation. This suggests that haptic feedback improved DT performance to task completion when acquiring a large sized target.

By evaluating the computed ANOVA results, the difference in DT between each haptic condition was significant. Shown in Table 6.2, we found more than 8 tasks with p values less than 0.05 for all comparisons between the assessed haptic conditions. In particular, DT under both hard and soft feedback conditions compared to selection with no feedback resulted in 9 and 8 tasks with significantly better DT results. Differences between hard and soft haptic conditions led to 9 tasks where DT was significantly less when selecting hard targets. These results show that difference types of haptic feedback affected DT to task completion.

DT performance for target sizes SelectL against SelectS:

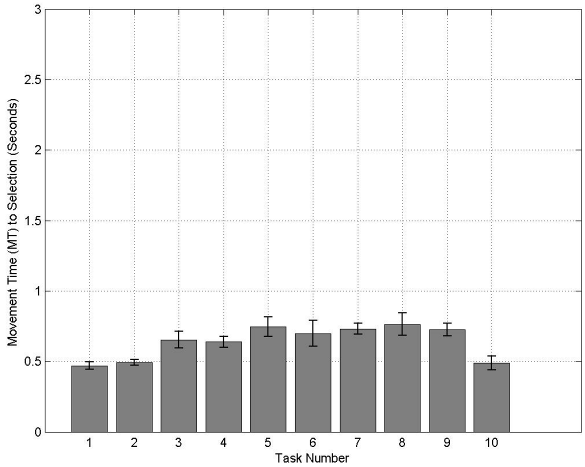
Selection with a large target resulted in less DT taken to task completion in compared to SelectS. In Table 6.3, for SelectL compared to SelectS DT was on average less by: 0.085m using hard feedback, 0.095m using soft feedback, and 0.124m using no feedback conditions. These differences were less than 1 standard deviation for each haptic condition. This suggests that a larger target size led to a small improvement in DT to task completion over SelectS.

From the computed ANOVA results, we found that DT differences between each target size comparison were significant. Shown in Table 6.3, we found 9 tasks were DT performance was significantly different between each size comparison. Furthermore this was consistent for each haptic condition. As a result, this indicated that large target sizes improves DT performance for single selection tasks.

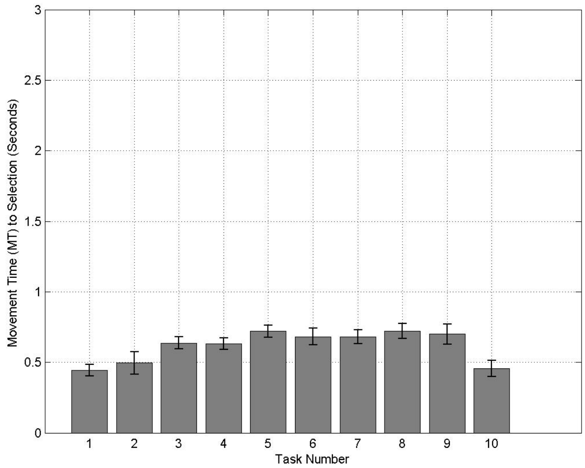
6.6.2.3 Velocity Taken (VT)

VT performance between haptic force feedback conditions:

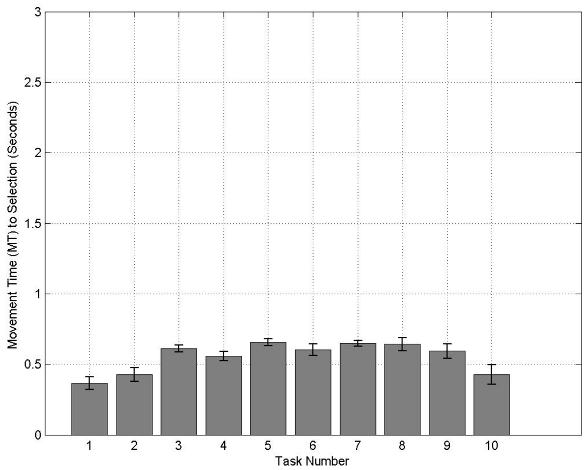
Participants selected a large target with greatest velocity under NoF conditions. On average VT performance to task completion was 0.751 m/s when selecting a target that exerted no feedback. Summarised



(a) Hard haptic condition

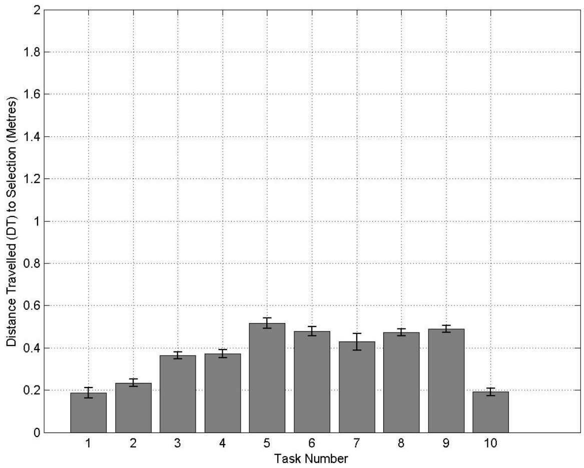


(b) Soft haptic condition

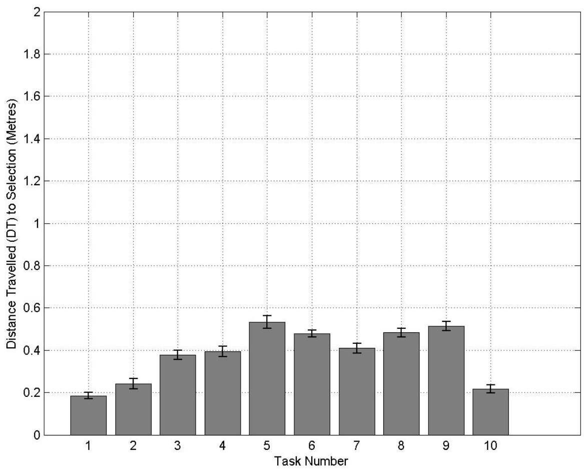


(c) NoF haptic condition

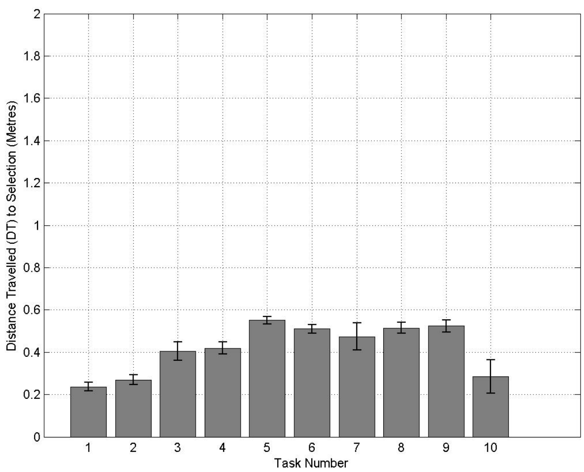
Figure 6.8: Selection of a large target (SelectL), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

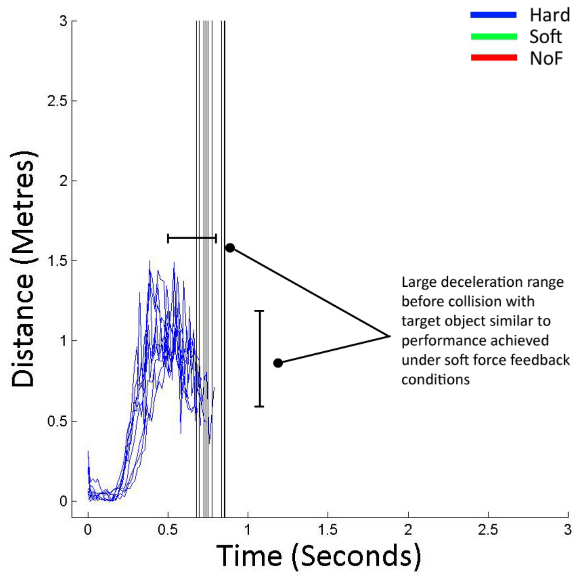


(b) Soft haptic condition

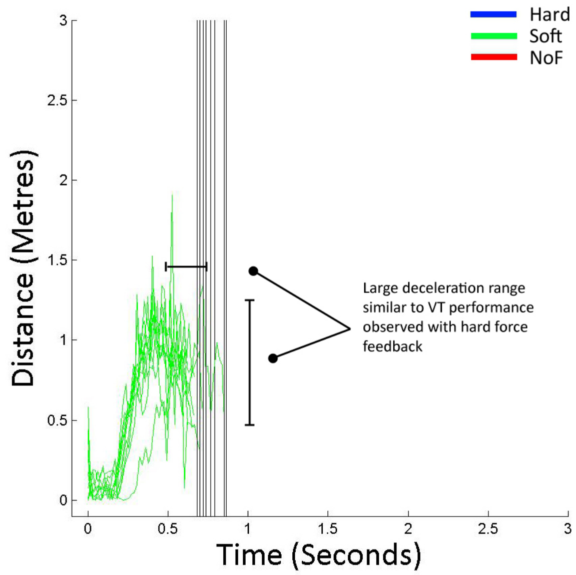


(c) NoF haptic condition

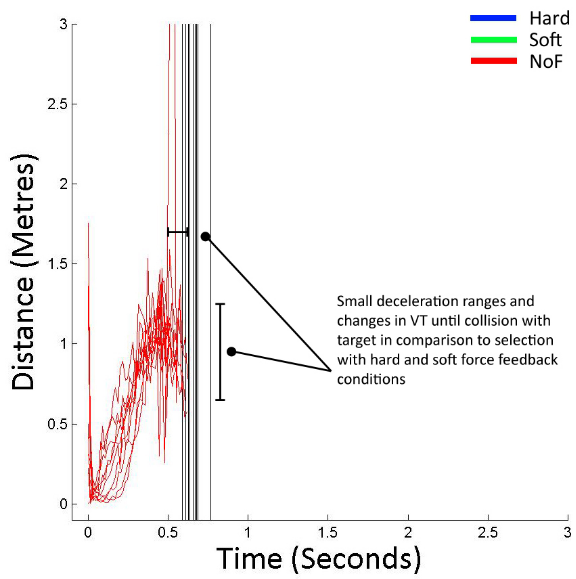
Figure 6.9: Selection of a large target (SelectL), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard force feedback condition

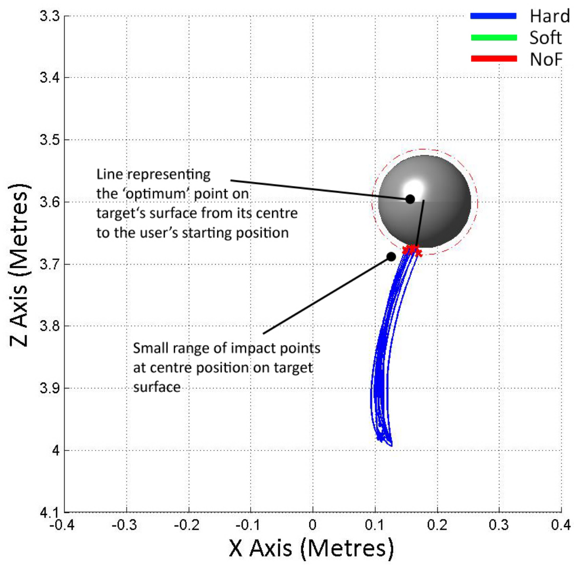


(b) Soft force feedback condition

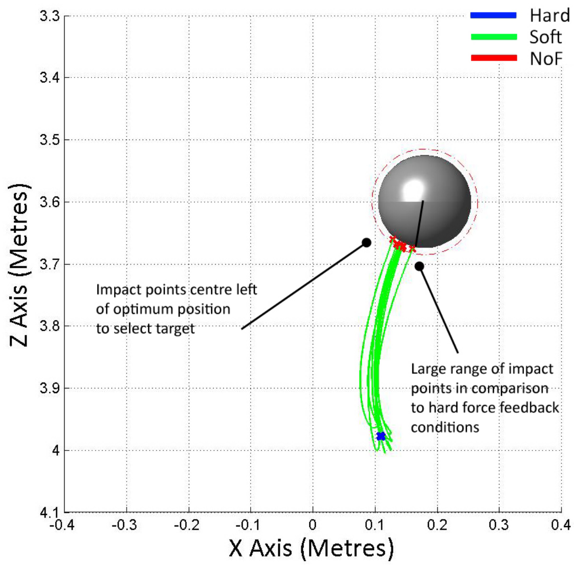


(c) No force feedback condition

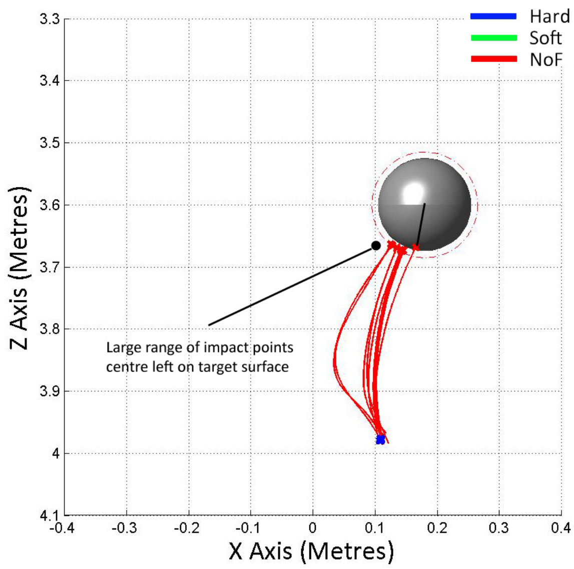
Figure 6.10: Selection of a large target (SelectL), Velocity profile for task number 119



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.11: Selection of a large target (SelectL), Trajectory profile for task number 112

in Table 6.2, VT under both hard and soft feedback conditions compared selection with no haptic was slower by 0.181 m/s and 0.145 m/s respectively. For comparisons between hard and soft feedback, participants selected targets with soft responses faster by 0.036 m/s. From Table 6.2, all differences between haptic conditions were greater than 1 standard deviation. These results suggest that for large targets VT performance was best under NoF conditions.

From the computed ANOVA results, we recorded large disparities in the VT performance achieved under each haptic condition. Shown in Table 6.2, VT results for both hard and soft condition compared to selection without haptic feedback lead to 7 tasks with p values less than 0.05. We also found 8 tasks, whereby selection using soft targets achieved significantly better VT results than those captured when under hard feedback conditions. This indicates that different haptic conditions affects VT performance when selecting a large target.

Based upon the velocity profiles, we found a clear difference in the deceleration patterns before selection for each haptic condition. Shown in Figure 6.10, compared to selection without haptic feedback, participants slowed down at a quicker rate under hard and soft conditions. Also, these profiles show that a high peak velocity was achieved under NoF conditions. This indicates that VT performance was best under NoF conditons when selecting a large single target.

VT performance for SelectL against SelectS:

For SelectL, VT was quickest under soft and NoF conditions. Shown in Table 6.3, for results against SelectS participants achieved a greater VT: by 0.021 m/s under hard feedback conditions, 0.040 m/s under soft feedback conditions, and 0.112 m/s under no feedback conditions. This suggests for large targets, haptic feedback condition had detrimental effect on VT performance.

Comparisons to SelectS led to large differences in VT performance. Shown in Table 6.3, we recorded more than 7 tasks whereby VT performance was better for SelectL than SelectS. This trend was also consistent for all haptic conditions. This demonstrates that participants were able to select a large target faster than SelectS.

6.6.2.4 Trajectory Analysis

Shown in Figure 6.11, we can see differences in the trajectory and impact points upon selection between with and without haptic feedback conditions. Specifically, when selecting targets with no feedback, participants used greater ‘arching’ motions rather than moving differently to the target. In comparison, trajectories using hard and soft targets were more direct. Further, the distribution of impact points was much greater under no feedback conditions compared to selection with hard and no feedback conditions. These plots demonstrate the differences in movement behaviour under hard, soft and no feedback conditions. In particular, they show that under NoF conditions extra effort was needed to select a single large target.

6.6.3 Discussion

When selecting a single target, we found that the variations in performances between haptic conditions changed with target size. In particular, the selection of large targets with haptic feedback had a detri-

Table 6.4: Summary of significant results between haptic conditions changes in size of a single target ('x' indicates conditions with significant differences between haptic conditions)

	SelectS			SelectL		
	MT	DT	VT	MT	DT	VT
Hard vs NoF	x	x			x	x
Hard vs Soft		x			x	x
Soft vs NoF	x	x			x	x

mental effect on the speed of movement to selection. To summarise these results, below we present a series of haptic feedback profiles for each target size. We also describe the changes in task efficiency with respect to haptic feedback as characterised by MT, DT, VT, impact points and trajectories taken to task completion:

Selection of a small target:

Table 6.5: Selection of small target (SelectS), Summary of results

Performance Marker	Result
MT	- Small variations in MT performance between each haptic feedback condition. - No significant differences in MT performance between soft and hard feedback conditions.
DT	- Shortest DT to task completion achieved under hard force feedback conditions. - Selecting targets that provided soft feedback response also resulted in better DT performances than results achieved under no force feedback conditions. Selection with no force feedback resulted in participants taking significantly longer paths to selection.
VT	-Best VT performance under no force feedback conditions.
SelectS vs SelectL	- Selecting a small target led to more time being taken to task completion compared to SelectL. This was consistent for each haptic condition. - Slower VT performances for SelectS compared to SelectL for each haptic condition. This shows that participants speed of movement was slower when asked to select a small target. - Between all three assessed haptic feedback conditions, we observed small changes in the deceleration curves and peak velocities before selection. - Slower VT performances for SelectS compared to SelectL for each haptic condition. This shows that participants speed of movement was slower when asked to select a small target.

When selecting a small target with haptic feedback, we found that participants were able to take shorter paths to task completion. As found in chapters 4 and 5, this suggests that without haptic feedback, extra movements are needed to overcome the lack of a physical response upon selection. However, there were significant differences in the time taken to select the target between haptic conditions. Specifically, the speed of movement was greater when selecting a small target without feedback. As shown by the VT results, participants moved with greater speed to select the single target. The velocity graphs also show that whilst there was a small difference between each haptic condition, the deceleration before contact under NoF conditions was less compared to selection with soft and hard feedback responses.

Nevertheless, as we found no difference in MT between each of the haptic conditions, the changes in VT and DT counter balanced each other.

Compared to selecting a large target, participants took slower and longer paths to task completion. The differences for MT, DT and VT between SelectS and SelectL were significant. As a result, this shows that selecting a small target had a detrimental effect on performance to task completion.

With respect to the Fitts' law results, the calculated results indicated a poor fit to the captured data. This shows that the selection behaviour observed when selecting a small target is not modelled well using Fitts' law.

Selection of a large target:

Table 6.6: Selection of small target (SelectL), Summary of results

Performance Marker	Result
MT	-Best MT results achieved under no force feedback conditions. -Worst MT results were found under hard force feedback conditions.
DT	-Least DT to task completion using hard feedback condition. Significant difference in DT behaviour between hard and soft feedback conditions and selection with no responses.
VT	-Quickest velocities found under no feedback conditions. -Hard feedback conditions resulted in the slowest VT performances. This suggests that haptic feedback with large targets reduces the speed of movement to selection.
SelectS vs SelectL	- MT performance for SelectL was quicker compared to SelectS for each haptic condition assessed. - Compared to SelectS, SelectL resulted in shorter DT results for each haptic condition. - For NoF conditions, VT for SelectL was better than SelectS.

When selecting a large single target, the time taken to complete the task was best without haptic feedback. However, as shown by the DT results, hard and soft haptic feedback led to shorter paths being taken to task completion. This is an interesting result, suggesting that whilst haptic feedback may improve the size of the paths taken to select the target, the difference in the speed of movement was significantly faster without haptic feedback leading to better MT performance. As there was also a difference between hard and soft feedback conditions, in particular for DT and VT results this indicated that the differences between each haptic condition were greater when selecting a large target. Whilst there may be a benefit in selecting a large target, having a haptic response can led to significantly slower movement speeds, affecting the time taken to select the target. Therefore, these results show that hard and soft haptic feedback response had a detrimental effect when selecting large targets, whereby participants selected targets with shorter distances but slower speeds. Interestingly, the estimates based upon a Fitts' law model provided a good correlation to the captured results.

Contrast to SelectS, selection with a large target provided significant differences in performance between each haptic condition. In particular, the MT results when selecting a large target with haptic feedback suggested this was detrimental to task efficiency. Conversely, against all size combinations, DT to task completion was best under haptic conditions and when moving to select a large target. Interestingly, the clearest distinction between haptic feedback condition and target size was found from the velocity profiles. When moving to select large targets, participants decelerated more sharply under hard and soft haptic conditions compared to results for SelectS leading to slower VT results. Therefore, this demonstrates that the effects when selecting targets with hard and soft haptic feedback was changed with target size.

To summarise:

- No difference in MT between haptic conditions when selecting a small target.
- Hard haptic responses led to significantly slower VT results when selecting a large target.
- Selecting a large target without haptic feedback achieved the best performance results.
- Hard and soft haptic responses led to shorter DT paths being taken to select both small and large targets.
- SelectL achieved best correlation to Fitts' law.

6.7 Results- Selection to Two Targets (Select2)

For a full list of trajectory and velocity graphs (see Apprendix C and attached CD under directory label 'Appendix C').

6.7.1 Selection of Two Small Sized Targets (SelectSS)

6.7.1.1 Movement Time (MT)

MT performance between haptic conditions:

For SelectSS, the quickest MT to task completion was achieved under NoF conditions. Depicted in Figure 6.12, the average MT to Select2,All for each haptic condition was: Hard, 1.603 seconds; Soft, 1.605 seconds; and NoF, 1.538 seconds. From Table 6.7, the difference in MT for Select2,All under NoF conditions compared to selection with hard and Soft responses was smaller by 0.065 seconds and 0.067 seconds respectively. For comparisons between hard and soft haptic conditions, selection with targets providing a hard response led to smaller MT results by 0.002 seconds. With respect to the standard deviation results, all these differences in MT to task completion were less 1. As a result, whilst participants selected two small targets with the least MT under NoF, there was little difference between haptic conditions.

By analysing the sub-tasks, we found that the biggest difference in MT between haptic conditions occurred when moving to the second target. Shown in Table 6.7, the difference in MT for Select2,2 under hard and soft feedback conditions compared to selection without haptic feedback was 0.043 seconds and 0.040 seconds respectively. In contrast, the same comparisons between haptic conditions for Select2,1 were smaller. For differences between hard and soft feedback conditions, these were small and less than 0.005 seconds. Therefore, this suggests that when moving to select the second target, there was a greater benefit to MT performance when under NoF conditions.

By computing a set of ANOVA results, we analysed the significance of the observed MT differences between the haptic feedback conditions. In Table 6.7, we found only 1 out of 10 tasks where the difference in MT performance for Select2,All between all haptic feedback conditions resulted in a p-value less than 0.05 . For the individual subtasks, only 3 tasks were recorded indicating that Select2,2 with no responses produced significantly better MT results against selection with hard targets. Otherwise, for all other comparisons we did not find many tasks showing a significant difference in MT performance between haptic force feedback conditions. This indicates that there was no difference in MT between haptic conditions when selecting two small targets.

MT performance for SelectSS against other target size combinations:

Participants selected two small targets with the slowest MT in comparison to the other target size combinations to task completion. Shown in Table 6.8, the average difference in MT for SelectSS to Select2,All compared to the other target size combinations was slower, ranging from 0.200 seconds to 0.401 seconds. The biggest difference in MT was achieved when compared SelectSS to MT results for selection with SelectLL. This trend in MT was also found for each haptic feedback conditions. Therefore, this suggests that selecting two small targets is detrimental to MT performance compared to selection with larger targets.

From the computed ANOVA results, we found that the MT results for SelectSS were significantly different to selection with other target size combinations. Shown in Table 6.8, for the majority of size comparisons, more than 5 out of 10 tasks resulted in significantly slower MT performances under SelectSS for Select2,All. By also assessing the MT performance for the sub-tasks, MT results for Select2,1 and Select2,2 were also slower for SelectSS. Select2,2 for SelectSS resulted in significantly slower MT results in comparison to the same movement achieved with the other target size combinations. Other interesting observations include MT comparisons of Select2,1 for SelectSL. In this instance we found that the MT difference to SelectSS when selecting the first target was not significantly different under hard haptic conditions. This is interesting, suggesting that selecting a second large target could have detrimental impact to selection strategy. Altogether, these results highlight the detrimental impact of small targets on MT performance.

MT performance against ID:

To understand the MT behaviour across all the tasks, we plotted the results for each task against their ID. In Figure 6.15, we separated each of the graphs by their sub movements and task completion. From these results, we found that MT increased with ID for all haptic conditions. By assessing subfigures 6.15(b) and subfigures 6.15(c), we found that the relationship between MT and ID for hard and soft feedback conditions were similar. In contrast, for Select2,1 this was not the case whereby the MT relationship for hard and no force feedback was noticeably different to selection with soft responses. This suggests small variations in MT behaviour for Select2,1 when selecting targets with hard and no force feedback responses.

By calculating the residual values for each haptic feedback plot, we were able to evaluate the fit of the data set to the computed ID values. For task completion R^2 for hard, soft and no feedback conditions was 86%, 81% and 75% respectively. For Select2,2: hard, 84%; soft, 74%; and NoF, 71%. For Select2,1: hard, 56%; soft, 72%; and NoF, 24%. From these results, we found that selection under no force feedback conditions led to the worst fit with respect to ID. This was evident when selecting the first target for both hard and no feedback conditions. This suggests a Fitts' law model does not fit well to the selection behaviour observed when moving to select a small first target out of two. Overall, selection with soft feedback response achieved best the best fit to the computed ID values.

6.7.1.2 Distance Travelled (DT)

DT performance against haptic condition:

Participants took the shortest path to task completion when selecting targets that provided hard responses. Depicted in Figure 6.13, the average MT to Select2,All for each haptic condition was: hard, 0.815m; soft, 0.829m; and NoF, 0.921m. From Table 6.7, the difference in DT for Select2,All under hard haptic conditions compared to selection with soft and no feedback was smaller by 0.106m and 0.015m respectively. For comparisons between soft and NoF conditions, selecting targets with soft responses led to smaller DT results to task completion by 0.091m. Differences for both hard and soft haptic conditions against selection with no feedback were greater than 1 standard deviation. For comparisons hard and soft conditions, the difference in DT was less than 1 standard deviation. This demonstrates that selecting two small targets that provided haptic feedback resulted in shorter paths to task completion.

With respect to the sub-tasks, the biggest difference in DT between haptic conditions occurred at Select2,1. In particular, this was evident for comparisons between selection with and without haptic feedback. Shown in Table 6.7, the difference in DT for Select2,1 under both hard and soft conditions compared to selection with no feedback was smaller by 0.061m and 0.066m respectively. This trend was also evident for Select2,2 but smaller in size. For comparisons between hard and soft feedback conditions, the biggest difference in DT occurred at Select2,2 whereby participants to a shorter path when selecting targets with hard responses by 0.020m. This is an interesting result, suggesting that when moving to the second target different sized paths to selection were taken between hard and soft haptic conditions. With respect to the standard deviation results, differences in DT for Select2,1 between hard and soft conditions to selection with no feedback was greater than 1. For Select2,2, this was also true only for differences between hard and NoF conditions. For all other comparisons between haptic conditions the difference in DT was less than 1 standard deviation. Therefore, these results suggest that when moving to select the first target, shorter sized paths to selection are taken with haptic feedback conditions.

From the computed ANOVA results, they show a difference in DT between selection with and without haptic feedback. From Table 6.7, for Select2,All we found 4 and 3 tasks whereby using hard and soft feedback conditions produced significantly better DT than selection with no feedback. This difference in DT was also evident for Select2,1 and Select2,2. Conversely, with respect to comparisons between hard and soft force feedback conditions there were only a small number tasks with p values less than 0.05. This indicates that haptic feedback improves DT performance, whilst there was little difference between selection with hard and soft targets.

Table 6.7: Selection of two small targets (SelectSS), Average, standard deviation and ANOVA results for MT, DT and VT to task completion between haptic conditions (n=10 for each haptic condition, and highlighted text indicates significant results)

Haptic condition:	Average performance for all tasks								
	MT			DT			VT		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
Hard	0.914	0.689	1.603	0.497	0.317	0.815	0.544	0.461	0.508
Soft	0.919	0.686	1.605	0.492	0.337	0.829	0.536	0.492	0.517
NoF	0.892	0.646	1.538	0.557	0.363	0.921	0.625	0.562	0.599
	Standard deviation for all tasks								
Hard	0.082	0.183	0.253	0.053	0.023	0.024	0.350	0.345	0.482
Soft	0.145	0.171	0.285	0.051	0.029	0.028	0.200	0.347	0.290
NoF	0.144	0.184	0.280	0.085	0.063	0.032	0.456	1.125	0.664
	Average difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.023	0.043	0.065	-0.061	-0.044	-0.106	-0.081	-0.102	-0.091
(Hard - Soft)	-0.005	0.003	-0.002	0.005	-0.020	-0.015	0.008	-0.031	-0.009
(Soft - NoF)	0.027	0.040	0.067	-0.066	-0.025	-0.091	-0.089	-0.071	-0.082
	Standard deviation of difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.110	0.069	0.118	0.049	0.038	0.059	0.095	0.077	0.104
(Hard - Soft)	0.100	0.091	0.165	0.023	0.031	0.046	0.042	0.028	0.029
(Soft - NoF)	0.126	0.118	0.198	0.045	0.038	0.058	0.089	0.078	0.096
	ANOVA results- Number of tasks whereby difference in performance between haptic conditions led to $p < 0.05$								
Hard vs NoF	1	3	1	5	4	4	7	5	7
Hard vs Soft	1	0	1	0	1	2	0	1	1
Soft vs NoF	0	1	1	4	3	3	4	3	5

Table 6.8: Selection of two small targets (SelectSS), Average difference in MT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

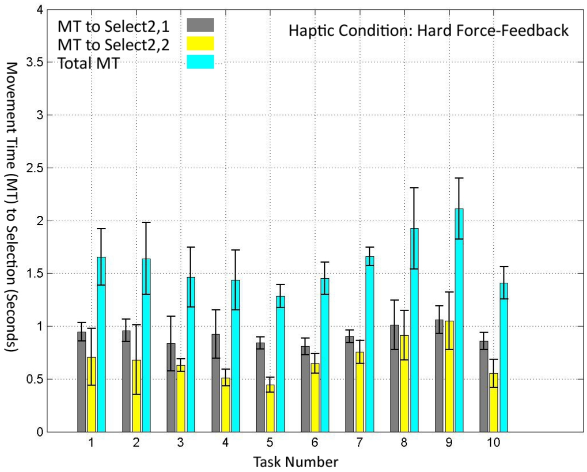
Size comparison	Average difference in MT between target size combinations for each haptic condition (Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSS - SelectLS)	0.204	0.169	0.373	0.199	0.135	0.335	0.235	0.092	0.327
(SelectSS - SelectSL)	0.029	0.175	0.204	0.029	0.195	0.224	0.044	0.186	0.229
(SelectSS - SelectLL)	0.179	0.171	0.350	0.203	0.230	0.434	0.230	0.220	0.449
	Standard deviation of difference in MT between target size combinations for each haptic condition (Seconds)								
(SelectSS - SelectLS)	0.107	0.173	0.229	0.145	0.185	0.292	0.175	0.171	0.266
(SelectSS - SelectSL)	0.108	0.216	0.278	0.196	0.234	0.345	0.195	0.202	0.309
(SelectSS - SelectLL)	0.126	0.229	0.331	0.179	0.228	0.384	0.209	0.260	0.401
	ANOVA results- Number of tasks where difference in MT between target size combinations led to $p < 0.05$								
SelectSS vs SelectLS	9	7	9	8	5	8	9	6	7
SelectSS vs SelectSL	2	5	3	3	6	7	2	8	6
SelectSS vs SelectLL	7	8	7	7	9	8	6	7	7

Table 6.9: Selection of two small targets (SelectSS), Average Difference in DT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

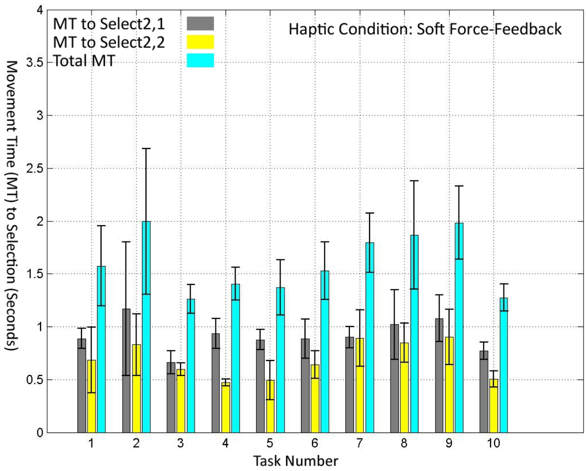
Size comparison	Average difference in MT between target size combinations for each haptic condition (Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSS - SelectLS)	0.079	0.051	0.130	0.066	0.030	0.096	3.985	-0.081	3.904
(SelectSS - SelectSL)	0.039	0.059	0.098	0.022	0.075	0.097	3.168	0.074	3.242
(SelectSS - SelectLL)	0.078	0.036	0.115	0.071	0.035	0.105	2.469	0.014	2.483
	Standard deviation of difference in DT between target size combinations for each haptic condition (Metres)								
(SelectSS - SelectLS)	0.103	0.123	0.161	0.115	0.128	0.179	5.543	0.106	5.548
(SelectSS - SelectSL)	0.114	0.164	0.200	0.128	0.170	0.221	6.547	0.166	6.559
(SelectSS - SelectLL)	0.116	0.176	0.262	0.115	0.177	0.267	8.153	0.182	8.114
	ANOVA results- Number of tasks where difference in DT between target size combinations led to $p < 0.05$								
SelectSS vs SelectLS	9	8	8	7	8	8	4	4	0
SelectSS vs SelectSL	8	8	9	7	10	8	4	8	5
SelectSS vs SelectLL	8	7	9	7	8	9	3	5	5

Table 6.10: Selection of two small targets (SelectSS), Average difference in VT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

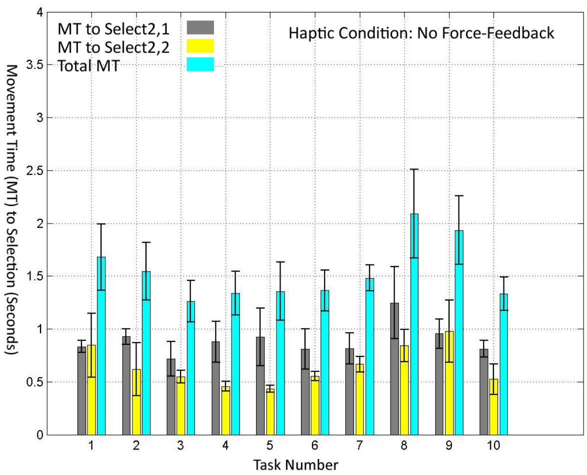
Size comparison	Average difference in VT between target size combinations for each haptic condition (Metres/Second)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSS - SelectLS)	-0.037	-0.041	-0.078	-0.041	-0.072	-0.114	-0.055	-0.280	-0.335
(SelectSS - SelectSL)	0.026	0.051	0.077	0.021	0.073	0.093	-0.801	0.066	-0.735
(SelectSS - SelectLL)	-0.017	-0.038	-0.054	-0.032	-0.055	-0.087	-0.051	-0.132	-0.184
	Standard deviation of difference in VT between target size combinations for each haptic condition (Metres/Second)								
(SelectSS - SelectLS)	0.077	0.188	0.156	0.086	0.188	0.148	0.087	0.199	0.159
(SelectSS - SelectSL)	0.074	0.181	0.162	0.078	0.195	0.177	2.619	0.195	2.610
(SelectSS - SelectLL)	0.078	0.172	0.198	0.071	0.169	0.179	0.098	0.208	0.240
	ANOVA results- Number of tasks where the difference in VT between target size combinations led to $p < 0.05$								
SelectSS vs SelectLS	6	8	7	5	7	5	6	8	7
SelectSS vs SelectSL	5	6	6	7	8	5	3	5	4
SelectSS vs SelectLL	7	8	7	4	7	7	6	7	6



(a) Hard haptic condition

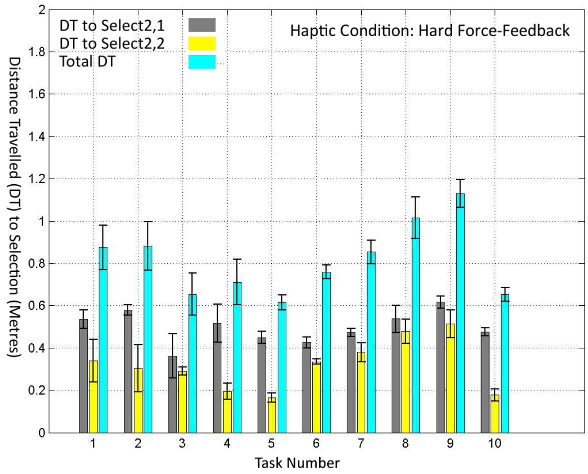


(b) Soft haptic condition

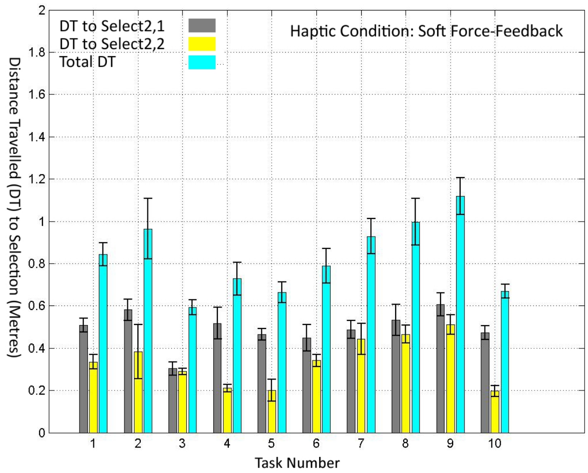


(c) NoF haptic condition

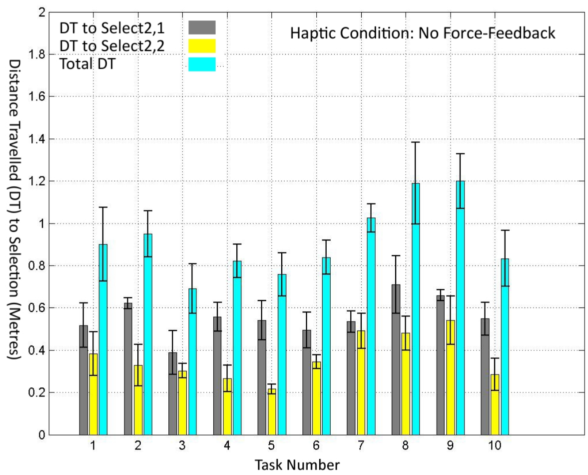
Figure 6.12: Selection of two small targets (SelectSS), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

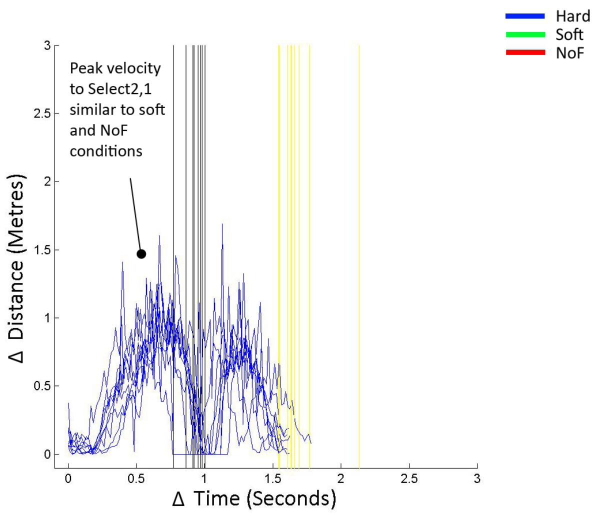


(b) Soft haptic condition

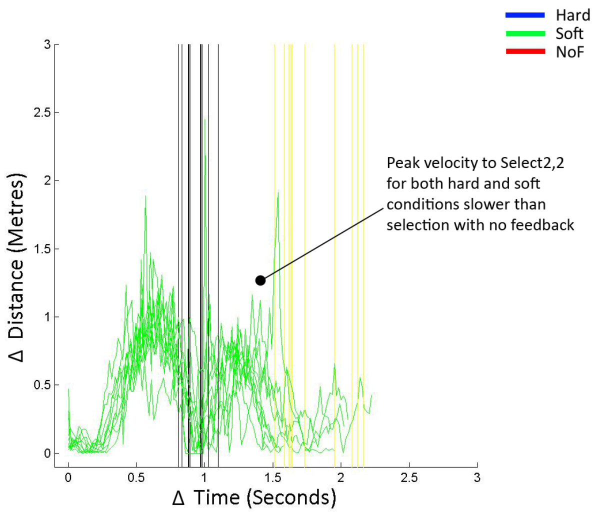


(c) NoF haptic condition

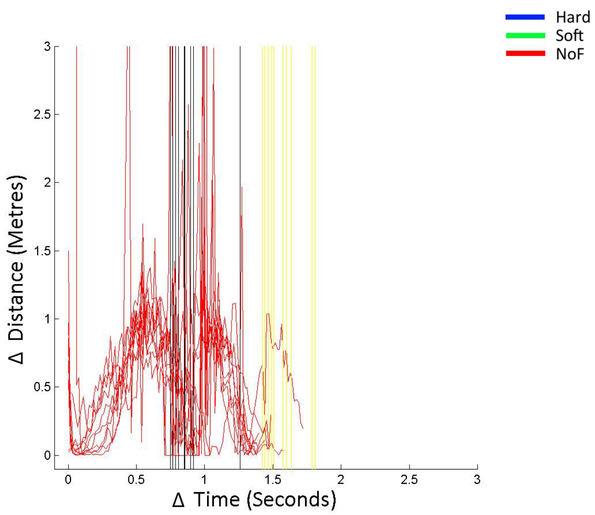
Figure 6.13: Selection of two small targets (SelectSS), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

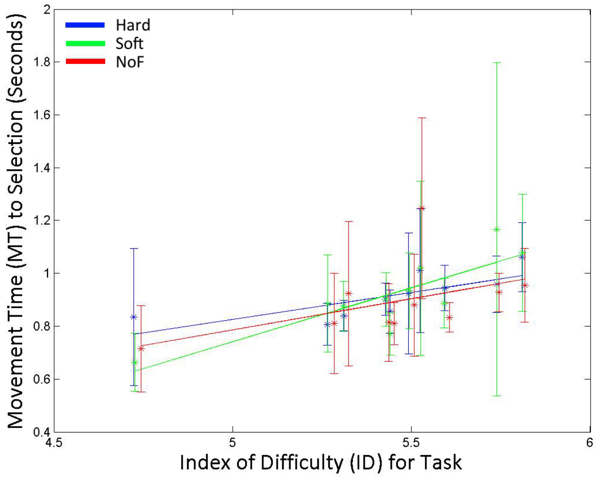


(b) Soft haptic condition

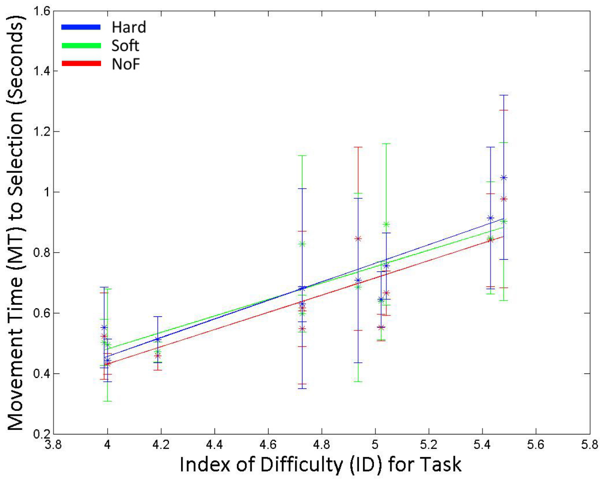


(c) NoF haptic condition

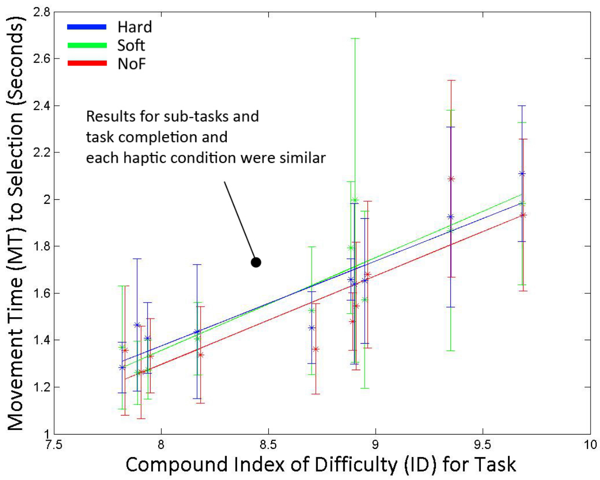
Figure 6.14: Selection of two small targets (SelectSS), Velocity profile for task number 7



(a) Select2,1

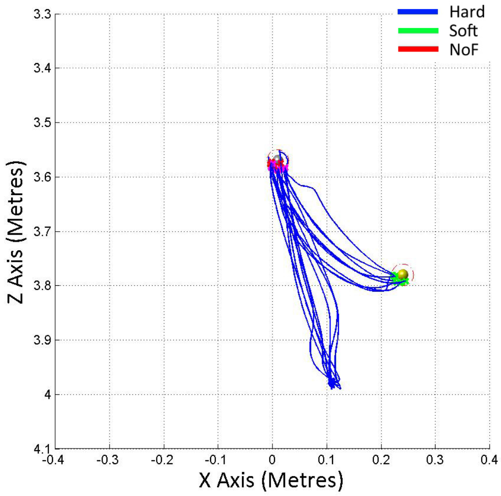


(b) Select2,2

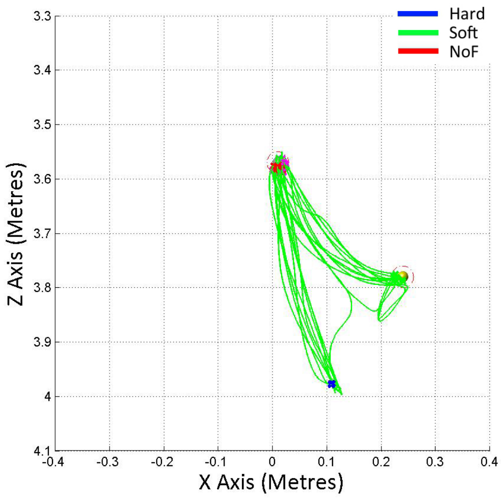


(c) Select2,All

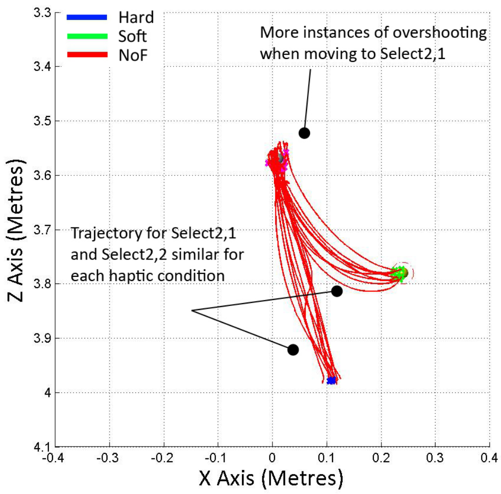
Figure 6.15: Selection of two small targets (SelectSS), MT against ID for each haptic condition



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.16: Selection of two small targets (SelectSS), Trajectory profile for task number task 6

DT performance for SelectSS against other target size combinations:
SelectSS achieved larger DT results in comparison to the majority of other size combinations. From Table 6.9, this performance gap for Select2,All ranged from 0.097m against SelectSL under soft conditions to 3.904m for SelectLS under no feedback conditions. Further assessment of the individual sub-movements showed that the biggest disparity with respect to target size mainly occurred at Select2,1, in particular for NoF conditions. From these results, this suggests that selecting two small targets leads to larger DT to task completion.

With respect to the computed ANOVA results, DT for SelectSS under hard and soft feedback conditions was significantly larger in comparison to the other size combinations. In Table 6.9, for Select2,All selection of two small targets providing either hard and soft responses resulted in 7 or more tasks with significantly different DT results. In contrast, selection under no force feedback conditions was less, less than 4 for task completion. This is a interesting result, suggesting the interaction between DT and target size is affected by haptic feedback.

6.7.1.3 Velocity Taken (VT)

VT performance between haptic feedback conditions:
Participants selected both targets with the greatest velocity under NoF conditions. The average VT to task completion for each haptic condition was: hard, 0.508 m/s; soft, 0.517 m/s; and NoF, 0.599 m/s. From Table 6.7, the difference in VT to Select2,All under NoF conditions compared to selection with hard and soft targets was faster by 0.091 m/s and 0.082 m/s respectively. For comparisons between hard and soft haptic conditions, the difference in VT was small by 0.009 m/s. With respect to the standard deviation results, all differences in VT to task completion between haptic conditions were less than 1. Therefore, these results show a small benefit in VT performance when selecting targets without haptic feedback.

By analysing the sub-tasks, the average VT for both Select2,1 and Select2,2 was faster under NoF conditions. From Table 6.7, VT for Select2,1 under NoF conditions compared to selection with hard and soft responses was faster by 0.081 m/s and 0.089 m/s respectively. For Select2,2, the difference in VT for between hard and NoF conditions was larger, whilst this was not the case for comparisons between soft and NoF conditions. This is an interesting result, suggesting that under hard feedback conditions, movement to the second target was much slower compared to the same task when selecting soft targets. This is evident by the difference in VT between hard and soft conditions increasing from 0.008 m/s for Select2,1 to 0.031 m/s for Select2,2. Differences in VT between selection with and without haptic conditions were greater than 1 standard deviation. With respect to selection with hard and soft targets, the difference in VT was greater than 1 standard deviation only for Select2,2. This shows that VT performance was best under NoF conditions, in particular when moving to the second target.

By plotting the velocity profiles for each task, we were able to assess the peak velocity and acceleration curves for each haptic condition. Shown in Figure 6.14, whilst movement to Select2,1 was similar for each haptic condition, peak velocities to Select2,2 were greater when selecting targets with no feedback responses. As a result, this suggests that participants were able to retain greater speed throughout the selection tasks under NoF haptic conditions.

From the computed ANOVA results, the difference in VT performance between selection with and without haptic feedback was significant. Summarised in Table 6.7, results for Select2,All under hard and soft conditions compared selection without haptic feedback led to 7 and 5 tasks with significantly slower results respectively. With respect to difference between hard and soft feedback conditions, we only found 1 task where there was a significant difference. Furthermore, by assessing the sub-movements, this trend was also consistent for both Select2,1 and Select2,2. This confirms that VT performance for SelectSS is affected by selection with haptic force feedback.

VT performance for SelectSS against other target size combinations:
Against the majority of target size combinations, VT results for SelectSS were slower to task completion. Except for results against SelectSL, in Table 6.10, the difference in VT ranged from 0.054m/s to 0.735m/s in slower VT results for SelectSS compared to SelectLS and SelectLL over each haptic condition. Interestingly, this difference in VT performance changed depending on feedback condition, whereby the largest disparity in VT performance was found under no force feedback conditions. Other observations include smaller VT differences to task completion for SelectSS in comparison to SelectSL under hard and soft force feedback conditions, whereby SelectSS achieved better results under soft and hard feedback conditions. This suggests that participants were able to select two small targets faster than SelectSL. For all other conditions, these results show the when selecting two small targets participants took less VT to task completion.

From the computed ANOVA data sets, we found that the slower VT performances for SelectSS were significantly different in comparison to the other size combinations. Shown in Table 6.10, for at least half of the assessed tasks, under both hard and soft conditions the VT difference for SelectSS was significantly slower to the other selection combinations. As a result, this show that small target sizes has a negative effect on VT performance expect for comparisons to SelectSL.

6.7.1.4 Trajectory Analysis

In Figure 6.16, we can see slight differences in movement behaviour between selection using hard, soft and no feedback responses. In particular, we found that participants took more efficient lines to Select2,2, and spent less effort selecting the first target under both hard and soft feedback conditions compared to selection with no responses. As discussed, this led to better DT performances. Nevertheless, as VT performance when selecting targets with both hard and soft haptic feedback was slower this meant MT to task completion was greater, similar to selection with targets that provided no feedback. For a full list of trajectory graphs go to Appendix C.

6.7.2 Selection of a Small then Large Sized Target (SelectSL)

6.7.2.1 Movement Time (MT)

MT performance between haptic force feedback conditions:

For SelectSL, MT performance was best under no feedback conditions. In Figure 6.17, the average MT to task completion when selecting targets with hard, soft and no feedback conditions were: 1.399 seconds, 1.381 seconds and 1.308 seconds. From Table 6.11, selection with targets that exerted hard and soft feedback were 0.091 seconds and 0.072 seconds slower respectively in comparison to no feedback conditions. Unlike other size combinations such as SelectSS, this difference to task completion between both haptic feedback conditions against no selection with no responses was greater than 1 standard deviation. In contrast, MT differences between hard and soft conditions was less than 1 standard deviation. These results suggest that for SelectSL, haptic feedback lead to increased MT results.

With respect to the sub-tasks, there was a difference in MT performance between Select2,1 and Select2,2. Shown in Table 6.11, for Select2,1 the difference under best performing no feedback conditions in comparison to selection with hard and soft responses was less than 1 standard deviation. Conversely for Select2,2, the difference between selection with and without haptic feedback was greater than 1 standard deviation. This suggests that haptic feedback had a detrimental effect on MT when moving from the first target to the second.

From the computed ANOVA results, selection with hard force feedback resulted in longer MT results. In Table 6.11, for comparisons between selecting both targets with hard responses to those that provided no feedback resulted in significantly slower MT results in 4 out 10 tasks. With respect to selecting targets that exerted soft force feedback upon selection, the MT difference in comparison to using no feedback conditions was worse in only 2 tasks, and better in 1 task against results for hard feedback conditions. Analysis of MT differences under select2,1 and select2,2 equally demonstrated a small under of tasks where the MT difference between conditions was significant. As a result, this indicates that whilst there is a difference in MT performance when selecting hard targets to other feedback conditions for SelectSL, the significance of this effect was small.

MT performance for SelectSL against other target sizes:

SelectSL resulted in better MT results only against a few other size combinations. Shown in Table 6.12, regardless of the inclusion of a large target in its selection combination, MT performance for SelectSL was only better against results for SelectSS for all haptic conditions. In particular, the captured MT performance ranged from 0.229 seconds better MT against SelectSS to being slower by 0.220 seconds against SelectLL. From Table 6.12, these variations were within 1 standard deviation. As a result, this suggests that for task completion MT performance for SelectSL was better against SelectSS. Otherwise, MT performance was worse against SelectLS and SelectLL. This is an interesting result, suggesting that participants preferred selecting a large sized target first before moving onto a small object.

For differences between Select2,1 and Select2,2, MT performance to the second target was best against the majority of other size combinations. As Select2,2 was a large target, MT performance was better except for comparisons against SelectLL under soft and NoF conditions. However, from Table 6.12, these differences were less than 1 standard deviation. Conversely for select2,1, MT was longer when comparing SelectSL to SelectLS and SelectLL. As this difference was greater than 1 standard deviation and consistent for each haptic condition, this suggests an interesting trade-off in MT performance whereby a smaller first target affects performance to a larger second target compared to other target size combinations.

From the computed ANOVA results, MT results for SelectSL were significantly different to other size combinations. From Table 6.12, for comparisons against SelectLL, we recorded at least 8 tasks where the MT performance to task completion for SelectSL was greater. Furthermore, this was also consistent for the individual sub movements and haptic conditions. For Select2,2 where MT performance was better under Select2,2 this was evident often in only 5 tasks out of 10. These results suggest that SelectSL led to poor MT performances.

MT performance against ID:

From Figure 6.20, we found that the relationship between MT and ID between selection under hard and soft haptic conditions were similar. For IDs, selection with no feedback achieved lower MT results. Interestingly for Select2,2, as shown in Figure 6.20(b), under soft haptic conditions at low IDs MT were similar to results achieved under NoF conditions. Nevertheless, as ID increased selection under soft feedback conditions were similar to results when selecting hard targets. This indicates that when moving to select a large target, different haptic feedback conditions have an effect on MT performance.

By calculating the residual values for each haptic feedback plot, we were able to evaluate the fit of the data set to the computed ID values. For task completion R^2 for hard, soft and no feedback conditions was 83%, 59% and 67% respectively. For Select2,2: hard, 88%; soft, 87%; and NoF, 90%. For Select2,1: hard, 31%; soft, 21%; and NoF, 20%. From these results, we found that selection under no force feedback conditions led to the worst fit with respect to ID especially for Select2,1. Poor correlation results were also found for Select2,1 under hard and soft haptic conditions. However, for Select2,2 this was not the case with results above 87% for all three haptic conditions. This is an interesting result, suggesting that a Fitts' law model does not estimate selecting a small first target well. However, the results suggest that movement between a small then large target follows a Fitts' law model.

6.7.2.2 Distance Travelled (DT)

DT performance against haptic condition

For SelectSL, participants took the least distance to task completion when selecting targets that exerted hard feedback responses. Depicted Figure 6.18, the computed average performance when selecting hard targets was 0.719m. For targets that exerted soft cues the average path size was 0.732m, whilst for conditions with no feedback cues was 1.560m. Summarised in Table 6.11, the difference in DT performance when selecting targets with hard and soft feedback responses resulted in participants using less DT by 0.113m and 0.097m in comparison to selection with no feedback cues. With respect to differences between soft and hard feedback conditions this was small averaging only 0.016m. By evaluating the re-

Table 6.11: Selection of a small then large target (SelectSL), Average, standard deviation and ANOVA results for MT, DT and VT to task completion between haptic conditions (n=10 for each haptic condition, and highlighted text indicates significant results)

Haptic condition:	Average performance for all tasks								
	MT			DT			VT		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
Hard	0.735	0.518	1.253	0.418	0.266	0.684	0.568	0.514	0.546
Soft	0.715	0.456	1.171	0.426	0.308	0.734	0.596	0.675	0.626
NoF	0.662	0.427	1.088	0.456	0.445	0.900	0.688	1.042	0.827
	Standard deviation for all tasks								
Hard	0.106	0.109	0.169	0.052	0.029	0.027	0.314	0.660	0.531
Soft	0.100	0.122	0.185	0.090	0.047	0.053	0.486	0.360	0.487
NoF	0.115	0.113	0.195	7.533	0.104	0.071	38.915	0.797	0.577
	Average difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.053	-0.034	0.019	-0.038	-0.178	-0.216	-0.120	-0.528	-0.281
(Hard - Soft)	-0.009	-0.031	-0.041	-0.008	-0.041	-0.050	-0.027	-0.161	-0.081
(Soft - NoF)	0.063	-0.003	0.060	-0.029	-0.137	-0.166	-0.093	-0.368	-0.201
	Standard deviation of difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.021	0.041	0.051	0.012	0.035	0.039	0.031	0.077	0.031
(Hard - Soft)	0.036	0.054	0.074	0.011	0.014	0.015	0.028	0.044	0.026
(Soft - NoF)	0.023	0.072	0.079	0.010	0.040	0.045	0.015	0.066	0.026
	ANOVA results- Number of tasks whereby difference in performance between haptic conditions led to $p < 0.05$								
Hard vs NoF	8	0	1	10	10	10	9	10	10
Hard vs Soft	0	2	2	1	8	7	0	6	4
Soft vs NoF	5	1	1	7	9	9	9	10	10

Table 6.12: Selection of a small then large target (SelectSL), Average difference in MT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

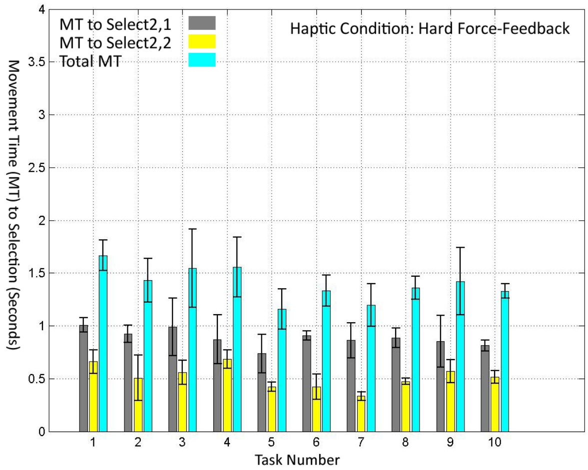
Size comparison	Average difference in MT between target size combinations for each haptic condition (Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSL - SelectSS)	-0.029	-0.175	-0.204	-0.029	-0.195	-0.224	-0.044	-0.186	-0.229
(SelectSL - SelectLS)	0.175	-0.006	0.169	0.170	-0.060	0.110	0.191	-0.093	0.098
(SelectSL - SelectLL)	0.149	-0.003	0.146	0.174	0.035	0.209	0.186	0.034	0.220
	Standard deviation of difference in MT between target size combinations for each haptic condition (Seconds)								
(SelectSL - SelectSS)	0.108	0.216	0.278	0.196	0.234	0.345	0.195	0.202	0.309
(SelectSL - SelectLS)	0.099	0.174	0.171	0.121	0.200	0.177	0.075	0.157	0.143
(SelectSL - SelectLL)	0.162	0.200	0.293	0.195	0.219	0.339	0.166	0.203	0.326
	ANOVA results- Number of tasks where the difference in MT between target size combinations led to $p < 0.05$								
SelectSL vs SelectSS	2	5	3	3	6	7	2	8	6
SelectSL vs SelectLS	7	7	6	7	7	6	8	5	2
SelectSL vs SelectLL	5	7	9	6	9	9	6	9	8

Table 6.13: Selection of a small then large target (SelectSL), Average difference in DT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

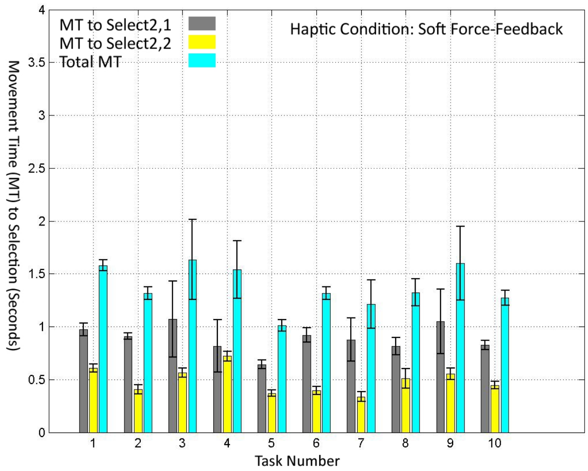
Size comparison	Average difference in DT between target size combinations for each haptic condition (Metres)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSL - SelectSS)	-0.039	-0.059	-0.098	-0.022	-0.075	-0.097	-3.168	-0.074	-3.242
(SelectSL - SelectLS)	0.040	-0.008	0.032	0.044	-0.045	-0.002	0.817	-0.155	0.662
(SelectSL - SelectLL)	0.039	-0.023	0.016	0.048	-0.041	0.008	-0.699	-0.060	-0.759
	Standard deviation of difference in DT between target size combinations for each haptic condition (Metres)								
(SelectSL - SelectSS)	0.114	0.164	0.200	0.128	0.170	0.221	6.547	0.166	6.559
(SelectSL - SelectLS)	0.109	0.161	0.148	0.100	0.166	0.141	2.386	0.159	2.431
(SelectSL - SelectLL)	0.171	0.176	0.244	0.180	0.186	0.278	5.594	0.189	5.545
	ANOVA results- Number of tasks where the difference in DT between target size combinations led to $p < 0.05$								
SelectSL vs SelectSS	8	8	9	7	10	8	4	8	5
SelectSL vs SelectLS	7	8	9	5	8	7	4	6	5
SelectSL vs SelectLL	9	10	9	7	10	9	5	8	6

Table 6.14: Selection of a small then large target (SelectSL), Average difference in VT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

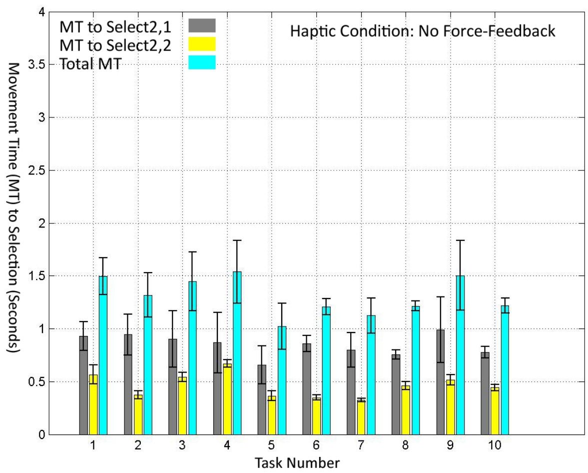
Size comparison	Average difference in VT between target size combinations for each haptic condition (Metres/Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectSL - SelectSS)	-0.026	-0.051	-0.077	-0.021	-0.073	-0.093	0.803	-0.067	0.736
(SelectSL - SelectLS)	-0.063	-0.092	-0.155	-0.062	-0.145	-0.207	0.746	-0.346	0.400
(SelectSL - SelectLL)	-0.042	-0.089	-0.131	-0.053	-0.127	-0.181	0.750	-0.198	0.552
	Standard deviation of difference in VT between target size combinations for each haptic condition (Metres/Seconds)								
(SelectSL - SelectSS)	0.074	0.181	0.162	0.078	0.195	0.177	2.619	0.196	2.612
(SelectSL - SelectSL)	0.094	0.260	0.203	0.102	0.285	0.246	2.610	0.302	2.711
(SelectSL - SelectLL)	0.125	0.209	0.176	0.129	0.228	0.212	2.662	0.224	2.621
	ANOVA results- Number of tasks where the difference in VT between target size combinations led to $p < 0.05$								
SelectSL vs SelectSS	5	6	6	7	8	5	3	5	4
SelectSL vs SelectLS	8	8	7	8	9	6	7	8	7
SelectSL vs SelectLL	7	10	6	9	8	7	6	9	7



(a) Hard haptic condition

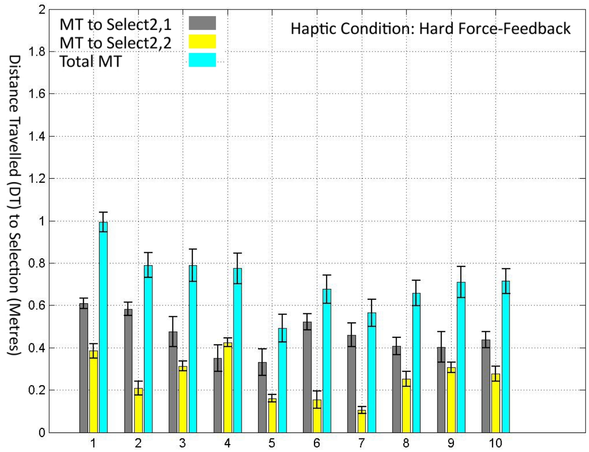


(b) Soft haptic condition

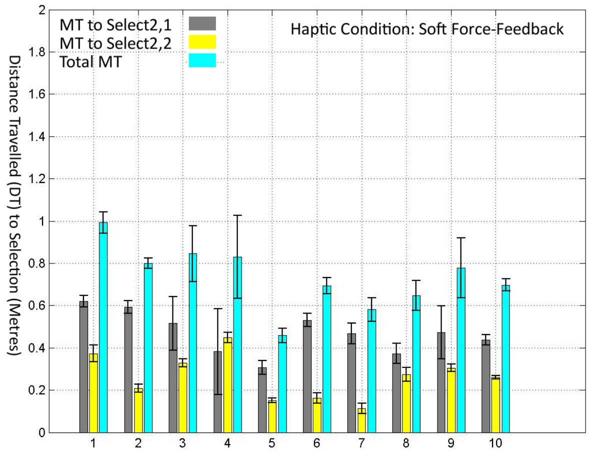


(c) NoF haptic condition

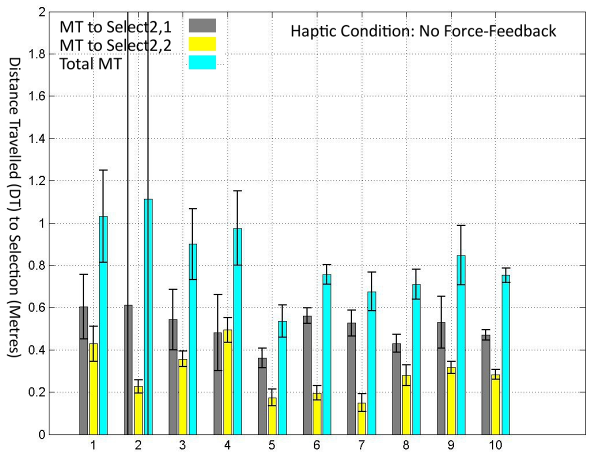
Figure 6.17: Selection of a small then large target (SelectSL), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

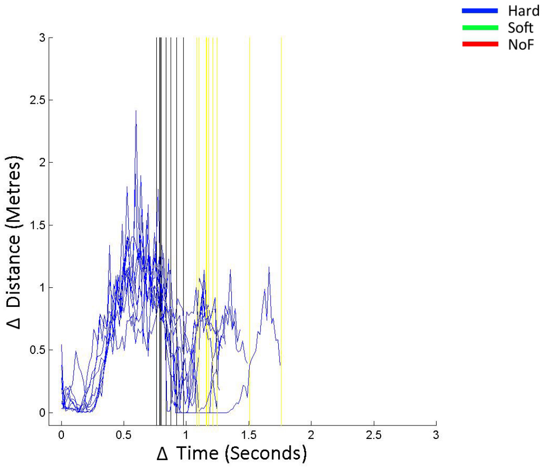


(b) Soft haptic condition

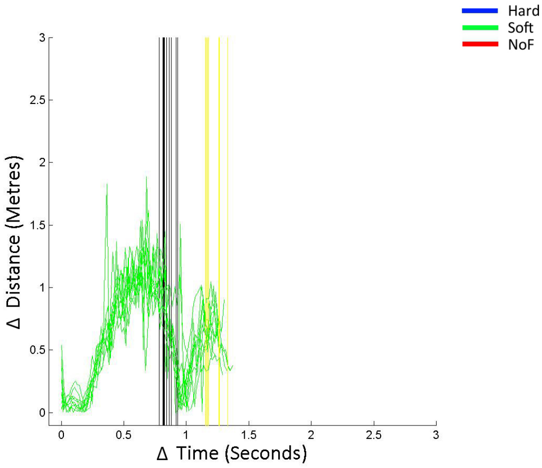


(c) NoF haptic condition

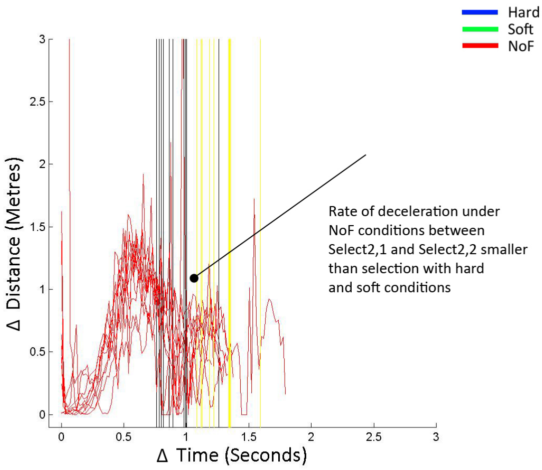
Figure 6.18: Selection of a small then large target (SelectSL), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

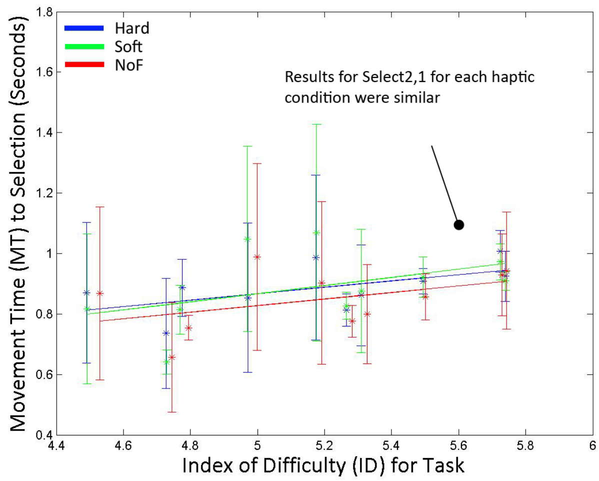


(b) Soft haptic condition

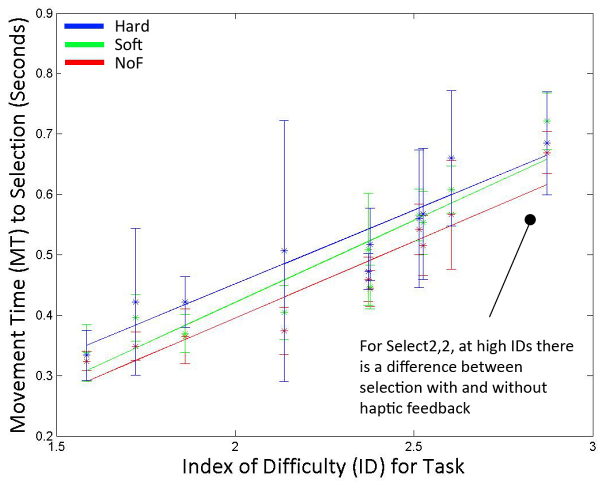


(c) NoF haptic condition

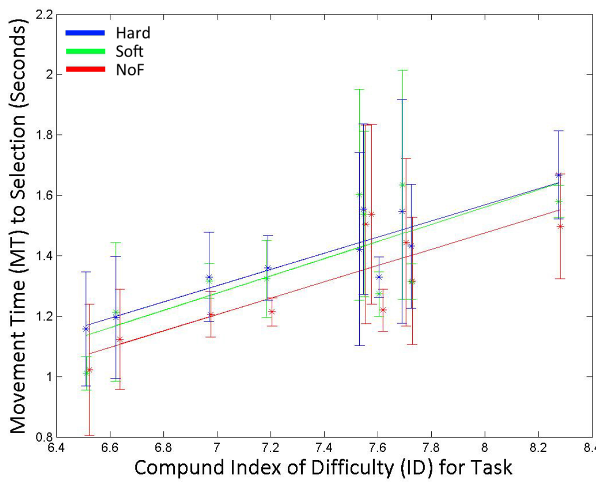
Figure 6.19: Selection of a small then large target (SelectSL), Velocity profile for task number 5



(a) Select2,1

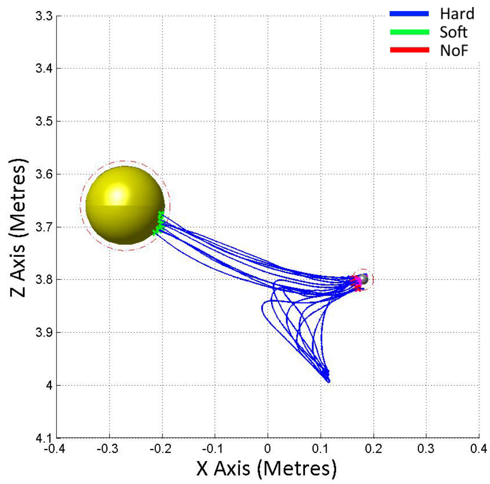


(b) Select2,2

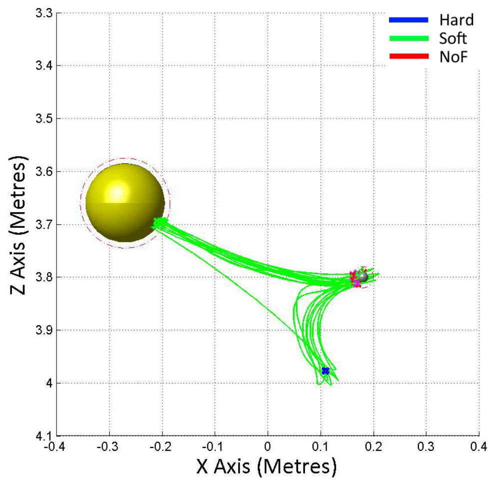


(c) Select2,All

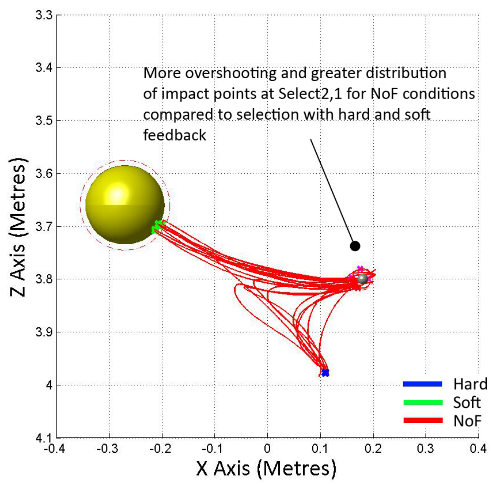
Figure 6.20: Selection of a small then large target (SelectSL), MT against ID for each haptic condition



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.21: Selection of a small then large target (SelectSL), Trajectory profile for task number 73

sults in Table 6.11, these variations in DT between selection with both soft and hard feedback responses against targets with no feedback were greater than 1 standard deviation. Conversely, for comparisons between hard and soft conditions this was less than 1. This suggests that haptic feedback benefits DT performance to task completion.

By analysing the individual sub-tasks, for both Select2,1 and Select2,2 DT performance was best when selecting hard and soft targets. Shown in Tables 6.11, whilst the DT difference between selection with and without haptic feedback was greater than 1 standard deviation for Select2,1, this behaviour was also evident for Select2,2. In contrast, and for both sub tasks, the difference in DT performance between hard and soft feedback conditions was small and within 1 standard deviation. This shows that haptic feedback improved DT performance for both task completion and sub-tasks.

From the set of ANOVA results, this also demonstrates the observed difference in DT selection with and without haptic feedback for each sub movement and task completion. In Table 6.11, there were 5 tasks from 10 where the DT performance was significantly better when comparing results achieved for both hard and soft feedback conditions to selection with no responses. For comparisons between hard and soft conditions, we only observed 1 task where selection performance was better using hard targets for Select2,2. Again, these results indicate that either soft and hard force feedback leads to better DT performance for SelectSL.

DT performance for SelectSL against other target sizes:

For task completion, when selecting targets with hard feedback responses DT for SelectSL was greater in comparison to the majority of other size combinations. Shown in Table 6.13, the DT achieved for SelectSL under hard feedback conditions was only better in comparison to SelectSS. When selecting targets with soft responses, DT performance for SelectSL was additionally better against SelectLS. With respect to selection with no feedback cue, SelectSL out performed DT results against SelectSS and SelectLL. This is an interesting result, suggesting an interaction between haptic feedback and target size.

By assessing the individual sub-tasks, DT performance to Select2,2 was better against all other size combinations. In contrast, from Tables 6.13, DT performances for Select2,1 were often larger for SelectSL with respect to the other size combinations. As a result, this demonstrates the effect of a small size target in increasing DT performance for SelectSL.

As shown by the ANOVA results, for both haptic conditions target size has a significant impact on DT performance. From Table 6.13, for each sub-movement we observed at least 5 tasks from 10 where DT performance was better or worse under SelectSL. In contrast to this trend, results achieved when selecting targets with no feedback, the difference in DT was often less than 5 tasks. Therefore, this suggests that whilst target size affects DT performance, when selecting targets with no feedback, the affect of this interaction was reduced compared to the behaviour observed with haptic responses.

6.7.2.3 Velocity Taken (VT)

VT performance between haptic force feedback conditions:

The quickest VT occurred when selecting targets that did not provide any haptic feedback. Shown in

Table 6.11, for task completion selection with hard and soft feedback conditions resulted in slower VT performances 0.123m/s and 0.104m/s respectively. Conversely, the disparity between selection with hard and soft feedback conditions was smaller, whereby participants selected soft targets on average 0.018m/s faster. Coupled with results summarised in Table 6.11, VT differences between selection with and without haptic feedback were greater than 2 standard deviations. For comparisons between hard and soft feedback conditions this was less than 1 standard deviation. This shows that VT performance was best when selecting targets with no feedback responses.

By analysing the individual sub-tasks, the observed disparity in VT between force feedback conditions was consistent for both Select2,1 and Select2,2. From Table 6.11, the VT difference between both hard and soft conditions to selection with no feedback was greater than 2 standard deviations for Select2,1 and Select2,2. In contrast, the VT difference between selection with hard and soft force feedback was less. As a result, this indicates under no force feedback conditions the VT was greater starting from selection of the first target in comparison to selection with either hard and soft responses.

From the computed ANOVA results, for task completion there was a clear distinction between selection with either hard and soft feedback and VT used with targets that exerted no responses. In Table 6.11, there were 7 tasks where VT performance was significantly slower when selecting targets providing hard and soft feedback responses in comparison to using no feedback conditions. In contrast, we did not record any differences in VT performance between selection with hard and soft feedback conditions. Interestingly, whilst this disparity between selection with and without haptic feedback is also evident in the sub-movements, the number of tasks indicating a significant difference in VT performances reduced by Select2,2. This suggests that for SelectSL, when moving to select a larger second target the difference in VT between feedback conditions reduces. Nevertheless, these results demonstrate that VT performance was best when selecting targets that do not exert haptic feedback.

By analysing the velocity profiles, we can see clear differences between selection with and without haptic feedback. Shown in Figure 6.19, the deceleration curves when moving to the second target were higher under hard and soft haptic conditions compared to selection without any feedback. Also, the peak velocities for Select2,2 under NoF conditions were higher. This demonstrates the advantages to VT performance for SelectSL without haptic feedback.

VT performance for SelectSL against other target sizes:

VT performance was worse for SelectSL in comparison to all other size combinations. Shown in Table 6.14, for task completion, the average VT when using hard and soft feedback conditions was slower in comparison to all other size combinations. Furthermore, this trend was also consistent for each sub-movement. In contrast, when selecting targets that exerted no feedback VT performance to task completion was faster for SelectSL against all other size combinations. This is interesting indicating a interaction between target size and haptic feedback condition on VT performance.

With respect to the individual sub-task, VT performance for Select2,2 was slower against all other size combinations. From Tables 6.14, the difference in VT performance when selecting a small target moving from a large target was lower against all size combinations. Furthermore, in comparison to results for Select2,1, VT performance was bigger. This suggests that selecting a larger second target reduces VT performance.

From the ANOVA results, results for SelectSL are distinctly different to all other size combinations. In terms of movements for Select2,2 the disparity in performance was large in comparison to selecting targets larger in size such as SelectLL. Other interesting results include VT comparisons to SelectSS suggesting that a larger second target with haptic feedback can also hinder VT performance.

6.7.2.4 Trajectory Analysis

By analysing the trajectory profiles, we can see clear differences in the movement behaviour between hard, soft and no feedback conditions. Specifically, as shown in Figure 6.21, whilst movement to the second target between all three conditions were similar, we observed changes in strategies when selecting the first target. Specifically, under hard and soft feedback conditions, participants used less distance by taking a more optimum line to selection compared to no feedback conditions were the gestures used were often more exaggerated. Furthermore, the range of impact points when using no feedback conditions was much greater and further away from the most efficient point to then move to the second target. In contrast, selection with hard and soft feedback conditions led to a reduced range in impact point distribution on Select2,1 and Select2,2. With this, we can see clear changes in selection strategy when using haptic and no feedback conditions.

6.7.3 Selection of a Large then Small Sized Target (SelectLS)

6.7.3.1 Movement Time (MT)

MT performance between haptic conditions:

For SelectLS,All there was little difference in MT between the assessed haptic conditions. Shown in Figure 6.22, whilst in some instances participants performed best without haptic feedback, the variations were small. From Table 6.15, the difference in MT to task completion under NoF conditions compared to selection with hard and soft targets was faster by 0.091 seconds and 0.072 seconds respectively. For comparisons between hard and soft feedback conditions, selection with hard targets was 0.041 seconds faster. With respect to the standard deviation results, the differences in MT to Select2,All for all comparisons between haptic conditions were less than 1. Therefore, this suggests that haptic feedback did not affect MT to task completion.

In terms of the sub-tasks, the biggest disparity between haptic conditions occurred when moving to select the second target. Shown in Table 6.15, for SelectLS2,2 the difference in MT under NoF conditions compared to selection with hard responses was smaller by 0.054 seconds. Conversely, the biggest disparity in MT when comparing NoF conditions to selection with soft targets occurred when moving to select the first target. These differences in MT for SelectLS2,1 were less than 1 standard deviation for all comparisons between haptic conditions. For SelectLS2,2, differences in MT were greater than 1 when comparing selection with and without haptic feedback. As these results are small, this suggests that haptic feedback did not affect MT performance between the sub-tasks.

From the ANOVA results, we found that the difference in MT to task completion between hard and NoF conditions was significant. From Table 6.15, the differences in MT to task completion under NoF conditions compared to selection with hard targets achieved 4 tasks with p values less than 0.05. For all other comparisons between haptic condition and sub-tasks we found fewer tasks demonstrating a significant difference in MT performance. As a result, whilst this suggests that hard target responses was detrimental to MT, for all conditions haptic feedback did not significantly affect user performance.

MT performance for SelectLS against other target sizes:

With respect to the effect of target size, MT for SelectLS was best in comparison to MT results achieved for SelectSS and SelectSL. From Table 6.16, this trend was also consistent for all three haptic conditions. Interestingly, participants preferred to select a large first then a small second target in comparison to the other size combinations. In particular, results comparing SelectLS against SelectSL lead to better MT performances to Select2,1 by 0.175 seconds respectively. In contrast, for movements to Select2,2, results achieved under selectLS were only better against SelectSS. Shown in Table 6.16, variations for Select2,1 were often greater than 1 standard deviation, whilst this was the opposite for Select2,2. This suggests a benefit to MT performance when selecting a large first, followed by a second small target.

By computing a set of ANOVA results, MT performance to task completion for SelectLS was significantly different against the majority of size combinations. In Table 6.16, 7 or more tasks indicated MT performance for SelectLS was significantly better than SelectSS. Overall, this trend was consistent for each of the three haptic conditions assessed suggesting SelectLS achieves better MT performances than SelectSS.

MT performance against ID:

To understand this behaviour in more detail, we plotted MT against the tasks difficulty index value. As shown in Figure 6.25, at low IDs we can see selection performance with no feedback responses is better than with both hard and soft conditions. Nevertheless, as ID increases the disparity between all three feedback conditions decreases. Interesting, whilst we found a clear disparity between selection with and without haptic feedback for select2,1, this was not the case for select2,2. This suggests that MT performance is best with large targets, but when selecting a small second target there is no difference in performance between feedback conditions.

With respect to the residual values, for task completion and sub-tasks these were estimated well to a Fitts' law model. For task completion R^2 for hard, soft and no feedback conditions was 86%, 79% and 79% respectively. For Select2,2: hard, 86%; soft, 91%; and NoF, 81%. For Select2,1: hard, 94%; soft, 79%; and NoF, 93%. Unlike SelectSL and SelectSS, these results suggest that a Fitts' law model gave good estimations for Select2,1 and Select2,2. Interestingly, we also do not observe the disparity between selection with and without haptic feedback previously found.

Table 6.15: Selection of a large then small target (SelectLS), Average, standard deviation and ANOVA results for MT, DT and VT to task completion between haptic conditions (n=10 for each haptic condition, and highlighted text indicates significant results)

Haptic condition:	Average performance for all tasks								
	MT			DT			VT		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
Hard	0.885	0.515	1.399	0.458	0.258	0.716	0.517	0.502	0.512
Soft	0.890	0.491	1.381	0.470	0.262	0.732	0.528	0.534	0.530
NoF	0.848	0.461	1.308	1.270	0.290	1.560	1.498	0.630	1.192
	Standard deviation for all tasks								
Hard	0.079	0.109	0.160	0.081	0.052	0.045	0.321	0.324	0.536
Soft	0.126	0.122	0.202	0.082	0.073	0.048	0.231	0.334	0.277
NoF	0.101	0.112	0.179	0.124	0.115	0.144	0.474	0.501	0.804
	Average difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.037	0.054	0.091	-0.054	-0.032	-0.113	-0.980	-0.128	-0.681
(Hard - Soft)	-0.005	0.024	0.019	-0.012	-0.004	-0.016	-0.011	-0.032	-0.019
(Soft - NoF)	0.042	0.030	0.072	-0.042	-0.028	-0.097	-0.970	-0.096	-0.662
	Standard deviation of difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.074	0.041	0.074	0.045	0.020	0.090	0.034	0.048	0.065
(Hard - Soft)	0.084	0.046	0.097	0.030	0.014	0.034	0.025	0.028	0.02
(Soft - NoF)	0.063	0.018	0.063	0.031	0.015	0.081	0.035	0.035	0.052
	ANOVA results- Number of tasks whereby difference in performance between haptic conditions led to $p < 0.05$								
Hard vs NoF	1	2	4	6	5	5	8	4	7
Hard vs Soft	0	2	1	0	1	0	0	1	0
Soft vs NoF	1	2	2	5	6	5	8	3	7

Table 6.16: Selection of a large then small target (SelectLS), Average difference in MT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

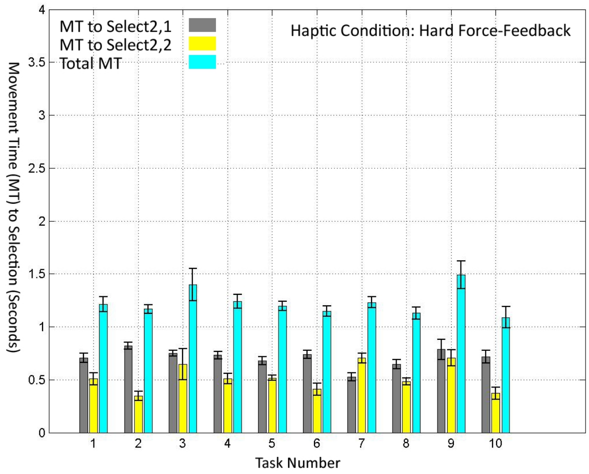
Size comparison	Average difference in MT between target size combinations for each haptic condition (Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLS - SelectSS)	-0.204	-0.169	-0.373	-0.199	-0.135	-0.335	-0.235	-0.092	-0.327
(SelectLS - SelectSL)	-0.175	0.006	-0.169	-0.170	0.060	-0.110	-0.191	0.093	-0.098
(SelectLS - SelectLL)	-0.026	0.002	-0.023	0.004	0.095	0.099	-0.005	0.128	0.122
	Standard deviation of difference in MT between target size combinations for each haptic condition (Seconds)								
(SelectLS - SelectSS)	0.107	0.173	0.229	0.145	0.185	0.292	0.175	0.171	0.266
(SelectLS - SelectSL)	0.099	0.174	0.171	0.121	0.200	0.177	0.075	0.157	0.143
(SelectLS - SelectLL)	0.163	0.167	0.229	0.164	0.185	0.244	0.164	0.172	0.251
	ANOVA results- Number of tasks where the difference in MT between target size combinations led to $p < 0.05$								
SelectLS vs SelectSS	9	7	9	8	5	8	9	6	7
SelectLS vs SelectSL	7	7	6	7	7	6	8	5	2
SelectLS vs SelectLL	7	7	7	5	7	5	5	6	6

Table 6.17: Selection of a large then small target (SelectLS), Average difference in DT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

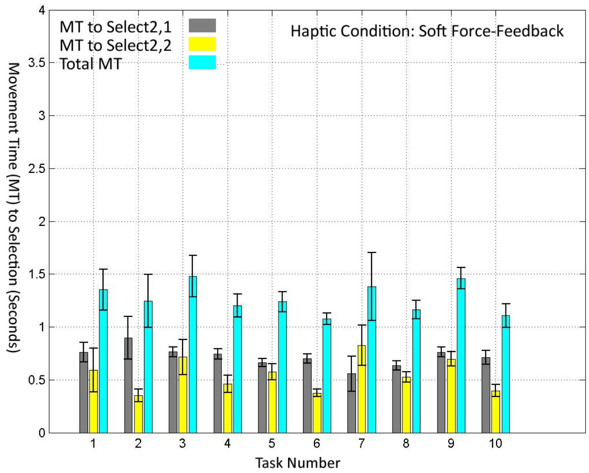
Size comparison	Average difference in DT between target size combinations for each haptic condition (Metres)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLS - SelectSS)	-0.079	-0.051	-0.130	-0.066	-0.030	-0.096	-3.985	0.081	-3.904
(SelectLS - SelectSL)	-0.040	0.008	-0.032	-0.044	0.045	0.002	-0.817	0.155	-0.662
(SelectLS - SelectLL)	-0.001	-0.015	-0.016	0.005	0.005	0.010	-1.516	0.095	-1.421
	Standard deviation of difference in DT between target size combinations for each haptic condition (Metres)								
(SelectLS - SelectSS)	0.103	0.123	0.161	0.115	0.128	0.179	5.543	0.106	5.548
(SelectLS - SelectSL)	0.109	0.161	0.148	0.100	0.166	0.141	2.386	0.159	2.431
(SelectLS - SelectLL)	0.170	0.163	0.218	0.176	0.167	0.236	4.797	0.186	4.774
	ANOVA results- Number of tasks where the difference in DT between target size combinations led to $p < 0.05$								
SelectLS vs SelectSS	9	8	8	7	8	8	4	4	0
SelectLS vs SelectSL	7	8	9	5	8	7	4	6	5
SelectLS vs SelectLL	7	8	8	6	6	9	7	5	7

Table 6.18: Selection of a large then small target (SelectLS), Average difference in VT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

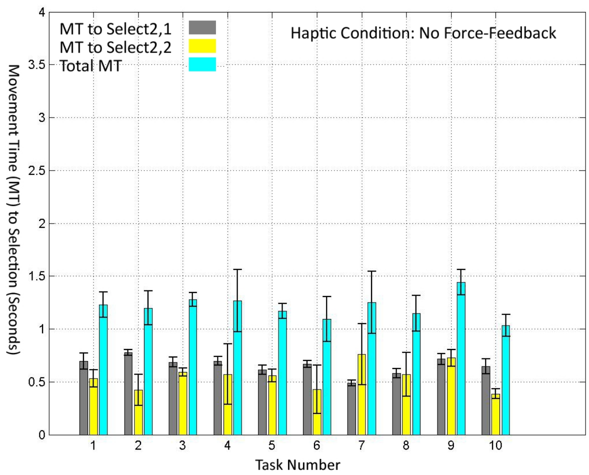
Size comparison	Average difference in VT between target size combinations for each haptic condition (Metres/Second)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLS - SelectSS)	-0.026	-0.051	-0.077	-0.021	-0.073	-0.093	0.803	-0.067	0.736
(SelectLS - SelectSL)	-0.032	-0.188	-0.220	-0.031	-0.236	-0.268	0.729	-0.398	0.332
(SelectLS - SelectLL)	-0.042	-0.089	-0.131	-0.053	-0.127	-0.181	0.750	-0.198	0.552
	Standard deviation of difference in VT between target size combinations for each haptic condition (Metres/Second)								
(SelectLS - SelectSS)	0.074	0.181	0.162	0.078	0.195	0.177	2.619	0.196	2.612
(SelectLS - SelectSL)	0.107	0.243	0.206	0.089	0.253	0.211	2.608	0.275	2.710
(SelectLS - SelectLL)	0.125	0.209	0.176	0.129	0.228	0.212	2.662	0.224	2.621
	ANOVA results- Number of tasks where the difference in VT between target size combinations led to $p < 0.05$								
SelectLS vs SelectSS	5	6	6	7	8	5	3	5	4
SelectLS vs SelectSL	5	7	7	7	8	8	6	8	8
SelectLS vs SelectLL	7	10	6	9	8	7	6	9	7



(a) Hard haptic condition

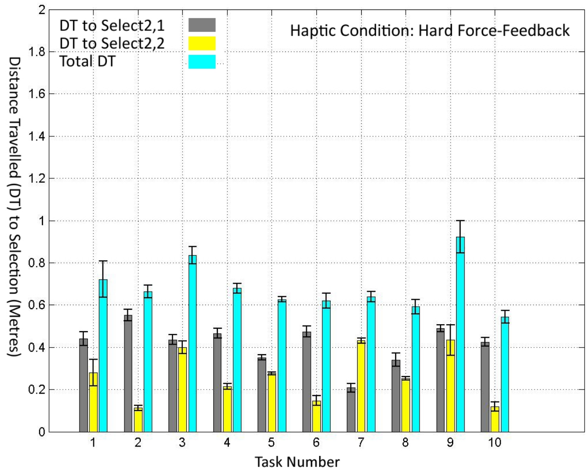


(b) Soft haptic condition

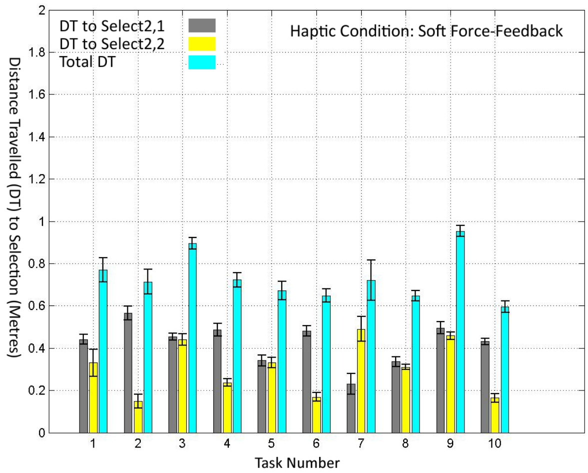


(c) No haptic condition

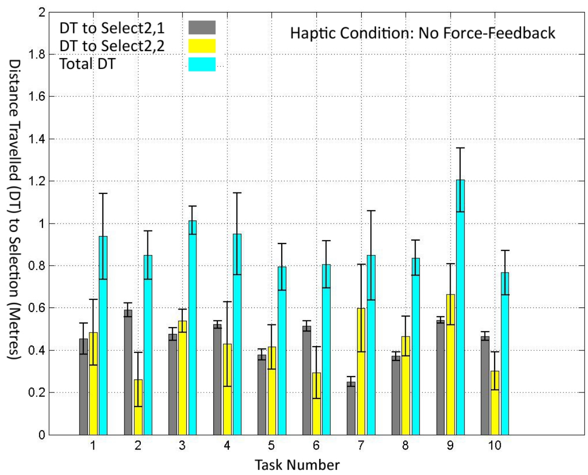
Figure 6.22: Selection of a large then small target (SelectLS), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

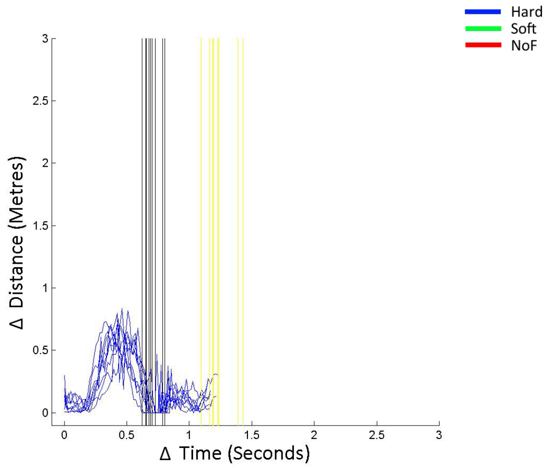


(b) Soft haptic condition

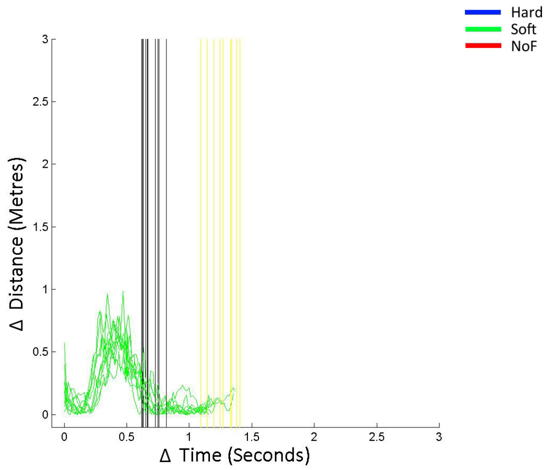


(c) NoF haptic condition

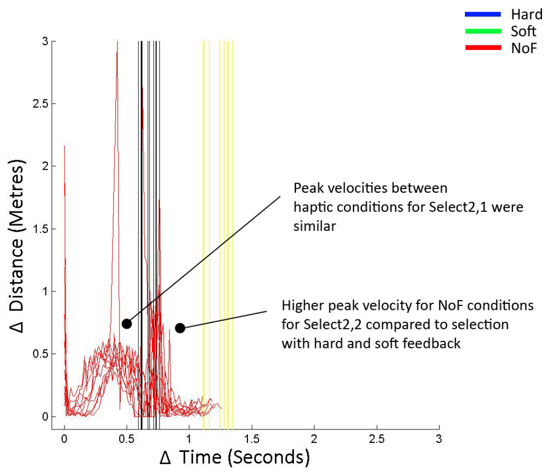
Figure 6.23: Selection of a large then small target (SelectLS), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

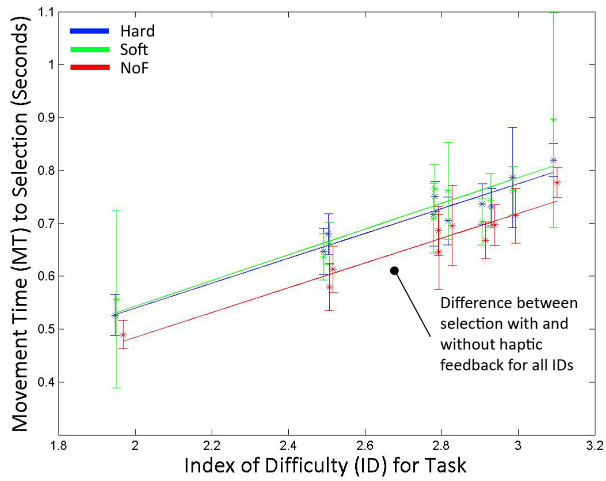


(b) Soft haptic condition

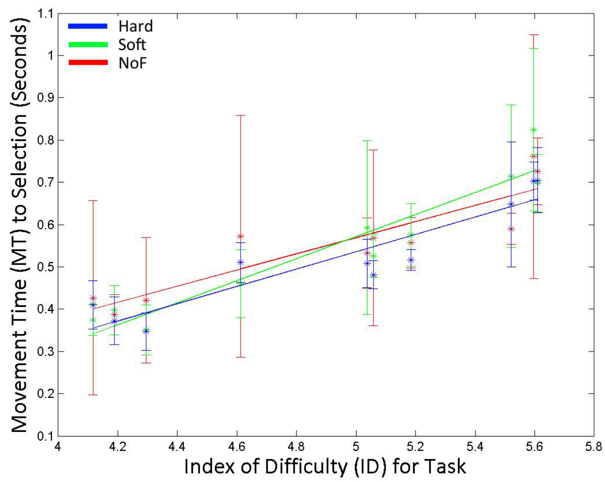


(c) NoF haptic condition

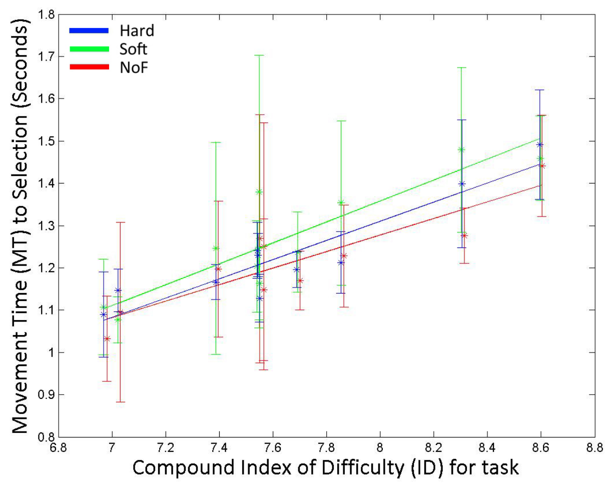
Figure 6.24: Selection of a large then small target (SelectLS), Velocity profile for task number 66



(a) Select2,1

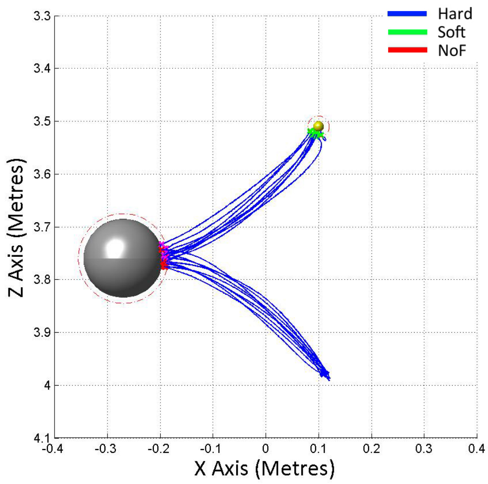


(b) Select2,2

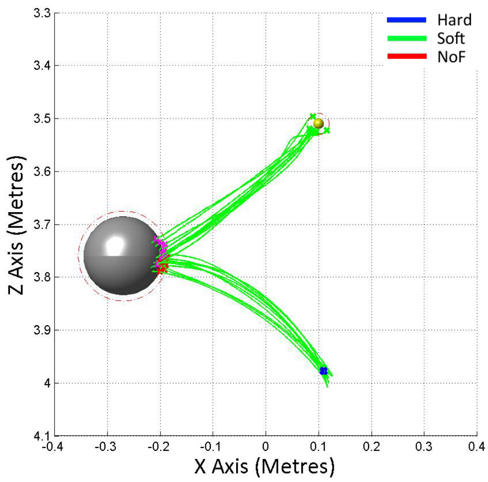


(c) Select2,All

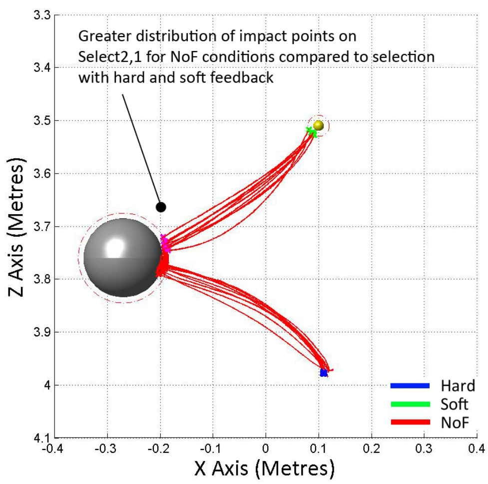
Figure 6.25: Selection of a large then small target (SelectLS), MT against ID for each haptic condition



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.26: SelectLS, Trajectory profile for task number 32

6.7.3.2 Distance Travelled (DT)

DT performance between haptic force feedback conditions:

Participants completed the task with the shortest distance under hard feedback conditions. Depicted in Figure 6.23, the average DT to task completion was: 0.716m when selecting hard targets, 0.732m when selecting soft targets, and 1.560m when selecting targets with no haptic responses. From Table 6.15, the difference in DT under hard and soft feedback conditions compared to selection with no responses was smaller by 0.216m and 0.166m respectively. With respect to DT differences between selection with hard and soft feedback, selecting hard targets achieved better results by 0.016m. These differences in DT to task completion under hard conditions compared to selection with no feedback were greater than 1 standard deviation. For all other comparisons between haptic conditions, the difference in DT was less than 1 standard deviation. This indicates that when selecting a large then small target, hard haptic conditions produced the least DT to task completion.

Between the sub-tasks, the greatest disparity in DT performance between haptic conditions occurred at Select2,1. In Table 6.15 the difference in DT between hard and soft conditions compared selection with no feedback was -0.054m and -0.042m respectively. For comparisons between hard and soft haptic conditions, participants selected hard targets on average with 0.012m less DT. For SelectLS2,2, we observed a similar trend between haptic conditions but the difference in DT was reduced. With respect to the standard deviation results, for comparisons between hard and soft conditions against selection with no feedback for SelectLS2,1 this was greater than 1. For SelectLS2,2, this was also true only for differences between hard and NoF conditions. For all other comparisons between haptic condition and sub-tasks the difference in DT was less than 1 standard deviation. This suggests that hard haptic responses led to shorter DT paths to the first and second targets.

The computed ANOVA results confirmed that DT performance was effected by haptic feedback. Shown in Table 6.15, for both hard and soft conditions compared to selection with no feedback the difference in DT to task completion led to 5 tasks with p values less than 0.05. Similarly, we found this result for Select2,1and Select2,2. For comparisons between hard and soft feedback conditions, there were no significant differences in DT to task completion. Therefore, this demonstrates that selection with haptic feedback led to shorter DT results compared to selection without haptic feedback for SelectLS.

DT performance for SelectLS against other target sizes:

In comparison to the small and medium target size combinations, DT performance was better for SelectLS. Shown in Table 6.17, and consistent for all three haptic conditions, DT for SelectLS was less to results under SelectSS and SelectSL. From Table 6.17, the biggest disparities in DT performance for SelectLS was against SelectSS. Therefore, this demonstrates that selection of large then small target led to better DT than targeting small target size combinations.

From the computed the ANOVA results, DT for SelectLS was significantly different to the other size combinations. Shown in Table 6.17, selection using hard targets recorded more than 7 tasks whereby by the DT difference between target size combinations were significantly different and consistent for each sub-movement. Similarly results under soft feedback conditions recorded 5 or more tasks where the DT performance of selectLS was different between other size combinations. In contrast, this was not the case when selecting under no feedback conditions. Whilst results to the first target were distinct, for Select2,2 and task completion results were often less than 5 tasks. Consequently, this highlights a difference between selection with and without haptic feedback and the effect of target size on DT performance.

6.7.3.3 Velocity Taken (VT)

VT performance between haptic conditions:

Participants performed best when selecting targets that did not exert any haptic feedback. Shown in Table 6.15, for task completion selection with hard and soft feedback conditions resulted in slower VT performances 0.123m/s and 0.104m/s respectively. Conversely, the disparity between selection with hard and soft feedback conditions was smaller, whereby participants selected soft targets on average 0.018m/s faster. Summarised in Table 6.15, VT differences between selection with and without haptic feedback were greater than 2 standard deviations. For comparisons between hard and soft feedback conditions this was less than 1 standard deviation. As a result, this showed that VT performance was best when selecting targets with no feedback responses.

By analysing the individual sub-tasks, the disparity in VT between feedback conditions was consistent for both Select2,1 and Select2,2. From Tables 6.15, the VT difference between both hard and soft conditions to selection with no feedback was greater than 2 standard deviations for Select2,1 and Select2,2. Nonetheless, From Table 6.15, whilst selection performance to Select2,1 results in a high number of tasks with significantly different VT results to selection with and without haptic feedback, this number reduces when selecting a small target. This suggests, that whilst there was a disparity in performance for Select2,2, selecting a smaller second object potentially reduced the difference in VT between feedback conditions.

From the computed ANOVA results, for task completion we found a clear distinction between selection with hard and soft feedback and VT used with targets that exerted no responses. In Table 6.15, we found 7 tasks where VT performance was significantly slower when selecting targets providing hard and soft feedback responses in comparison to using no feedback conditions. Conversely, there were no differences in VT performance between selection with hard and soft feedback conditions. Furthermore, as previously discussed, we also noticed a decrease in the number of different tasks between select2,1 and select2,2, suggesting selection of a smaller second target reduces the disparity in VT between haptic conditions. Therefore these results showed that VT performance was best when selecting targets that do not exert haptic feedback.

From the velocity profiles, we found distinct differences in the velocity to the Select2,2 between selection with and without haptic feedback. Shown in Figure 6.24, selection under NoF conditions led to large peak velocities for Select2,2. In contrast, under hard haptic conditions participants decelerated at a greater rate when moving select the first large target. Therefore, VT performances were best under NoF conditions as greater velocity could be carried between targets.

VT performance for SelectLS against other target size:

When selecting targets that exerted both hard and soft feedback responses VT performance was worse for SelectLS in comparison to all other size combinations. Shown in Table 6.18, for task completion, the average VT when using hard and soft feedback conditions was slower in comparison to all other size combinations. Furthermore, this trend was also consistent for each sub-task. In contrast, when selecting targets that exerted no feedback VT performance to task completion was faster for SelectLS against all other size combinations. As a result, this suggests the affect of target size on VT was different depending on haptic condition.

By assessing the results for the individual sub-movements, VT performance for Select2,2 was slower against all other size combinations. From Tables 6.18, we can see that the difference in VT performance when selecting a small target moving from a large target is lower against all size combinations. Furthermore, in comparison to results for Select2,1, they are all bigger in size. This showed that selecting a smaller second target reduces VT performance.

From the ANOVA results, results for SelectLS were distinctly different to all other size combinations. Shown in Table 6.18, we found that VT performance when selecting hard and soft targets was significantly slower all other size combinations. In terms of movements to Select2,2 the disparity in performance was large in comparison to selecting targets larger in size such as SelectLS. Other interesting results included VT compared to SelectSS suggesting that a larger first target with haptic feedback can also hinder performance.

6.7.3.4 Trajectory Analysis

By analysing the trajectory taken to task completion, we can see differences in the movement behaviour between selection with hard, soft and no feedback responses. As shown in Figure 6.26, the initial selection points and exit points on the first target changes with haptic feedback conditions. Specifically, whilst under hard feedback conditions the entry and exit points on the first target coincide. For soft and no feedback conditions, as participants are able to enter the first target and exit at different points the leads to different trajectories to the final target.

6.7.4 Selection of Two Large Sized Targets (SelectLL)

6.7.4.1 Movement Time (MT)

MT performance between haptic conditions:

MT to task completion was quickest under NoF conditions. Depicted in Figure 6.27, the average MT results for the 3 haptic conditions were: 1.253 seconds under hard haptic conditions, 1.171 seconds under soft haptic conditions, and 1.088 seconds under NoF haptic conditions. Shown in Table 6.19 MT under NoF conditions compared to selection with hard and soft feedback responses was slower by 0.165 seconds and 0.081 seconds respectively. With respect to the difference in MT between hard and soft feedback conditions, selection with hard targets was slower by 0.082 seconds. These difference in MT were greater than 1 standard deviation. Therefore, this suggests haptic feedback was detrimental to MT.

With respect to the sub-tasks, the biggest disparity in MT between haptic conditions occurred when moving to select the second target. From Table 6.19, the difference in MT at Select2,2 between selection with hard and NoF conditions was 0.091 seconds. In contrast, for comparisons between hard and soft and soft and NoF conditions, the difference in MT was smaller. For Select2,1, the largest difference in MT was between hard and NoF conditions. Interestingly, unlike Select2,2, the difference between selection with soft and no responses was larger suggesting a change in movement behaviour between haptic conditions. As result, this demonstrates different MT performances to task completion and sub-task depending on haptic conditions.

From the ANOVA results, we found that the observed differences in MT between haptic conditions were significant. From Table 6.19, MT to task completion under NoF conditions compared to selection with hard and soft responses resulted in 7 and 4 tasks with p values less than 0.05 respectively. For comparisons between hard and soft feedback conditions, selection with hard targets led to 4 tasks with significantly greater MT. With respect to the sub-tasks, we found a similar trend for Select2,1 and Select2,2 whereby we found 7 and 8 tasks with p values less than 0.05 respectively. Interestingly, for comparisons between hard and soft conditions when moving the first and second targets we found an increase in the number of tasks from 3 to 6. These results indicated that whilst hard responses increased MT. Altogether, there was a significant difference in MT performance between haptic conditions.

MT performance for SelectLL against other target size combinations:

For selectLL, MT performance varied depending on haptic condition. Shown in Table 6.20, selection performance was best using hard targets against SelectSS, and SelectLS. In contrast for soft and no feedback conditions, SelectLL was best against all other size combinations. From Table 6.20, differences against SelectSS were greater than 1 standard deviation. In general, SelectLL produced better MT results compared to size combinations with a small target.

With respect to the sub-tasks, we found interesting variations depending on haptic conditions. From Table 6.20, whilst selection to the second target was best against all size combinations under soft and no feedback conditions this was not the case for when selecting hard targets. In particular, MT performance was better except for SelectLS. This suggests that selecting two large targets with hard feedback had a negative impact on MT.

To confirm this trend, we computed a set of ANOVA results. Shown in Table 6.20, SelectLL produced distinct results to the other target size combinations. This result was also consistent for each haptic conditions.

MT performance against ID:

To assess the MT behaviour, we plotted these results against ID. As shown in Figure 6.30, as with other selection combinations, the behaviour to select2,1 and select2,2 are different. With regards to the MT behaviour for each haptic condition, whilst there is a constant gap between hard and no feedback conditions, behaviour under soft conditions is different. Whilst for low IDs it is similar to no feedback conditions, the gradient as ID increases was much less under no feedback conditions. For select2,2, results for soft feedback were similar to hard feedback responses for lower IDs, which then changed as ID increased. These plots demonstrate the difference in MT with respect to haptic condition.

By calculating the residual values for each haptic feedback plot, we were able to evaluate the fit of the data set to the computed ID values. For task completion R^2 for hard, soft and no feedback conditions was 79%, 92% and 85% respectively. For Select2,2: hard, 54%; soft, 85%; and NoF, 77%. For Select2,1: hard, 95%; soft, 92%; and NoF, 65%. The worst fit to the ID values occurred for Select2,2 under hard haptic conditions. This suggests that for movements between two large sized targets the Fitts' law model is not a good estimate for the behaviour observed. Equally, this was also evident for Select2,1 under NoF conditions. Interestingly, when moving to select the first target, a Fitts' law model resulted in good estimates to the observed behaviour. Again this suggests that the Fitts' law model does not consider aspects when moving from the first target into the second for hard and NoF haptic conditions.

6.7.4.2 Distance Travelled (DT)

DT performance between haptic force feedback conditions:

For SelectLL, the least DT to task completion was achieved under hard conditions. Depicted in Figure 6.28, the average DT to Select2,All for each haptic condition was: 0.700m under hard condition; 0.724m under soft condition; and 0.809m under NoF conditions. From Table 6.19, the difference in DT to Select2,All under NoF conditions compared to selection with hard and soft responses was greater by 0.109m and 0.084m respectively. With respect to differences between hard and soft conditions, selection with hard targets achieved less DT by 0.025m. These variations in DT for both hard and soft conditions were greater than 2 standard deviations. For comparisons between soft and hard feedback conditions, the difference in DT was greater than 1 standard deviation. Therefore, this showed that each haptic condition had a different effect on DT performance, whereby selecting hard targets achieved the best results.

With respect to the sub-tasks, we found the biggest disparity between haptic conditions occurred when moving to select the second target. Shown in Table 6.19, DT to Select2,2 under hard conditions compared to selection with soft and no haptic responses was smaller by 0.022m and 0.072m respectively. In contrast, for Select2,1 these differences in DT were smaller. With respect to the standard deviation results, comparisons between all haptic conditions for Select2,2 was greater than 1 standard deviation. For Select2,1 differences in DT between haptic conditions were less than 1. This is an interesting result suggesting that the disparity in DT between haptic conditions occurred when moving to select the second target.

From the ANOVA results, we found that the difference in DT between hard and NoF conditions were significant. From Table 6.19, for Select2,All the difference in DT in 9 tasks under hard conditions compared to selection with no feedback led to p values less than 0.05. Conversely, comparisons with soft conditions achieved only 4 tasks with significantly different DT against results when selecting with hard and no feedback responses. For Select2,2 the number of tasks indicating significantly different DT results were greater in comparison to results for Select2,1, in particular for differences between hard and soft feedback conditions. These results indicated that the DT performance under hard

Table 6.19: Selection of two large targets (SelectLL), Average, standard deviation and ANOVA results for MT, DT and VT to task completion between haptic conditions (n=10 for each haptic condition, and highlighted text indicates significant results)

Haptic condition:	Average performance for all tasks								
	MT			DT			VT		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
Hard	0.735	0.518	1.253	0.419	0.281	0.700	0.569	0.543	0.558
Soft	0.715	0.456	1.171	0.421	0.303	0.724	0.589	0.664	0.618
NoF	0.662	0.427	1.088	0.456	0.353	0.809	0.688	0.828	0.743
	Standard deviation for all tasks								
Hard	0.106	0.109	0.169	0.064	0.039	0.028	0.289	0.516	0.332
Soft	0.100	0.122	0.185	0.095	0.049	0.060	0.460	0.345	0.429
NoF	0.115	0.113	0.195	7.536	0.122	0.111	36.112	0.800	0.729
	Average difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.074	0.091	0.165	-0.037	-0.072	-0.109	-0.119	-0.285	-0.185
(Hard - Soft)	0.020	0.062	0.082	-0.003	-0.022	-0.024	-0.020	-0.122	-0.060
(Soft - NoF)	0.053	0.029	0.083	-0.034	-0.050	-0.084	-0.099	-0.163	-0.125
	Standard deviation of difference in performance between haptic conditions for all tasks								
(Hard - NoF)	0.047	0.064	0.089	0.072	0.050	0.051	0.053	0.063	0.048
(Hard - Soft)	0.030	0.051	0.056	0.024	0.024	0.030	0.025	0.033	0.024
(Soft - NoF)	0.059	0.031	0.061	0.060	0.041	0.041	0.050	0.061	0.049
	ANOVA results- Number of tasks whereby difference in performance between haptic conditions led to $p < 0.05$								
Hard vs NoF	7	8	7	5	7	9	9	7	9
Hard vs Soft	3	6	4	0	5	4	4	5	5
Soft vs NoF	5	4	4	4	5	4	8	5	7

Table 6.20: Selection of two large targets (SelectLL), Average difference in MT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

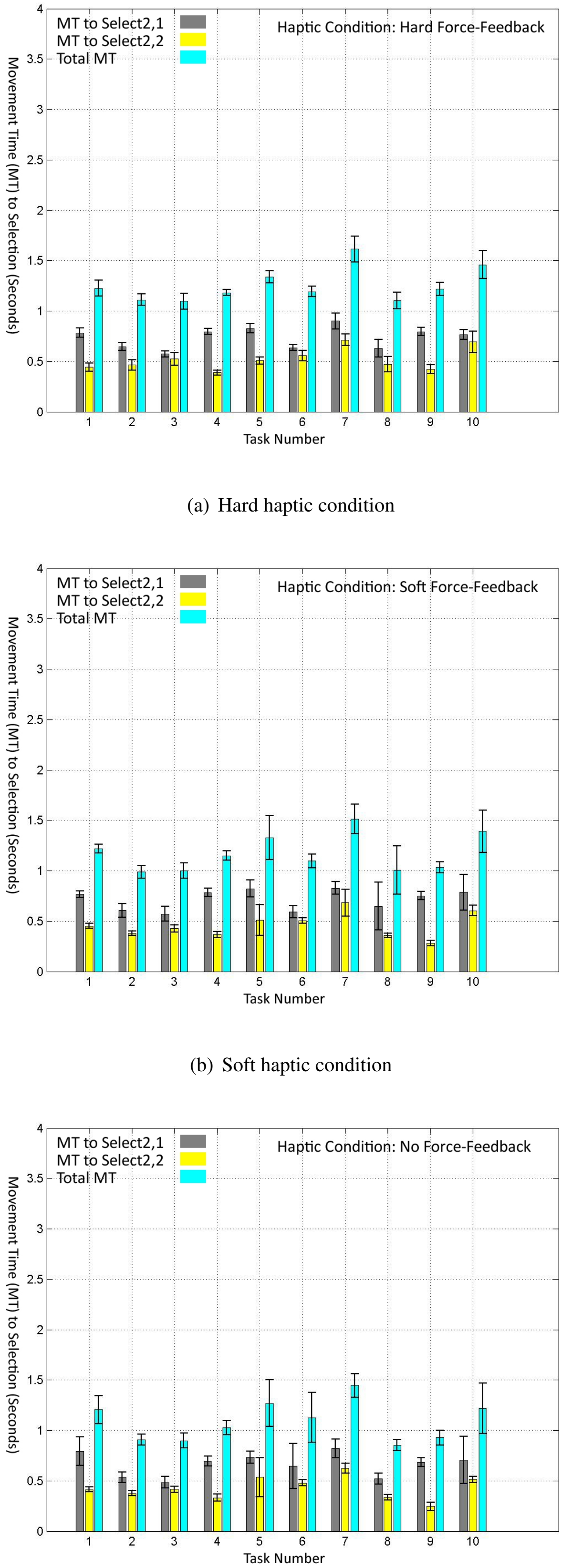
Size comparison	Average difference in MT between target size combinations for each haptic condition (Seconds)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLL - SelectSS)	-0.179	-0.171	-0.350	-0.203	-0.230	-0.434	-0.230	-0.220	-0.449
(SelectLL - SelectLS)	0.026	-0.002	0.023	-0.004	-0.095	-0.099	0.005	-0.128	-0.122
(SelectLL - SelectSL)	-0.149	0.003	-0.146	-0.174	-0.035	-0.209	-0.186	-0.034	-0.220
	Standard deviation of difference in MT between target size combinations for each haptic condition (Seconds)								
(SelectLL - SelectSS)	0.097	0.157	0.235	0.147	0.142	0.235	0.169	0.172	0.286
(SelectLL - SelectLS)	0.180	0.211	0.346	0.209	0.226	0.368	0.238	0.212	0.364
(SelectLL - SelectSL)	0.138	0.110	0.220	0.220	0.079	0.264	0.227	0.121	0.281
	ANOVA results- Number of tasks where the difference in MT between target size combinations led to $p < 0.05$								
SelectLL vs SelectSS	7	8	7	7	9	8	6	7	7
SelectLL vs SelectLS	7	7	7	5	7	5	5	6	6
SelectLL vs SelectSL	5	7	9	6	9	9	6	9	8

Table 6.21: Selection of two large targets (SelectLL), Average difference in DT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

Size comparison	Average difference in DT between target size combinations for each haptic condition (Metres)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLL - SelectSS)	-0.078	-0.036	-0.115	-0.071	-0.035	-0.105	-2.469	-0.014	-2.483
(SelectLL - SelectLS)	0.001	0.015	0.016	-0.005	-0.005	-0.010	1.516	-0.095	1.421
(SelectLL - SelectSL)	-0.039	0.023	-0.016	-0.048	0.041	-0.008	0.699	0.060	0.759
	Standard deviation of difference in DT between target size combinations for each haptic condition (Metres)								
(SelectLL - SelectSS)	0.116	0.176	0.262	0.115	0.177	0.267	8.153	0.182	8.114
(SelectLL - SelectLS)	0.170	0.163	0.218	0.176	0.167	0.236	4.797	0.186	4.774
(SelectLL - SelectSL)	0.171	0.176	0.244	0.180	0.186	0.278	5.594	0.189	5.545
	ANOVA results- Number of tasks where the difference in DT between target size combinations led to $p < 0.05$								
SelectLL vs SelectSS	8	7	9	7	8	9	3	5	5
SelectLL vs SelectLS	7	8	8	6	6	9	7	5	7
SelectLL vs SelectLL	10	8	10	9	9	10	6	7	7

Table 6.22: Selection of two large targets (SelectLL), Average difference in VT, standard deviation and ANOVA results between target size combinations (n=10 for each haptic condition, and highlighted text indicates significant results)

Size comparison	Average difference in VT between target size combinations for each haptic condition (Metres/Second)								
	Hard			Soft			NoF		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
(SelectLL - SelectSS)	0.017	0.038	0.054	0.032	0.055	0.087	0.053	0.131	0.184
(SelectLL - SelectLS)	-0.020	-0.003	-0.023	-0.009	-0.017	-0.026	-0.004	-0.148	-0.151
(SelectLL - SelectSL)	0.042	0.089	0.131	0.053	0.127	0.181	-0.749	0.198	-0.552
	Standard deviation of difference in VT between target size combinations for each haptic condition (Metres/Second)								
(SelectLL - SelectSS)	0.078	0.172	0.198	0.071	0.169	0.179	0.098	0.208	0.240
(SelectLL - SelectLS)	0.124	0.251	0.195	0.131	0.257	0.201	0.143	0.316	0.269
(SelectLL - SelectSL)	0.125	0.209	0.176	0.129	0.228	0.212	2.661	0.223	2.621
	ANOVA results- Number of tasks where the difference in VT between target size combinations led to $p < 0.05$								
SelectLL vs SelectSS	7	8	7	4	7	7	6	7	6
SelectLL vs SelectLS	8	9	9	5	8	6	5	6	5
SelectLL vs SelectSL	7	10	6	9	8	7	6	9	7

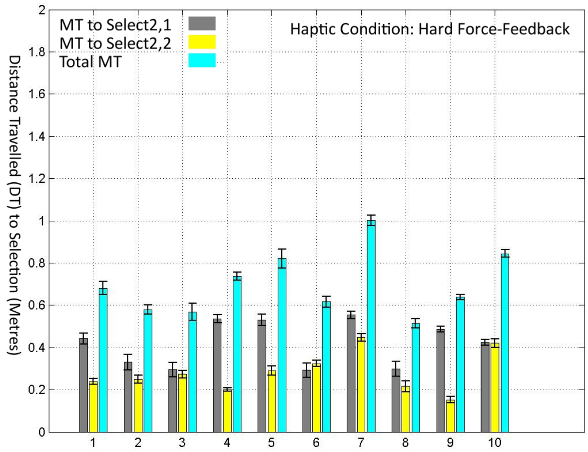


(a) Hard haptic condition

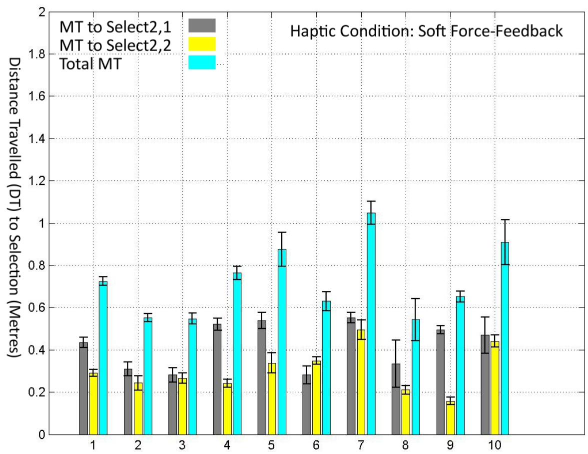
(b) Soft haptic condition

(c) NoF haptic condition

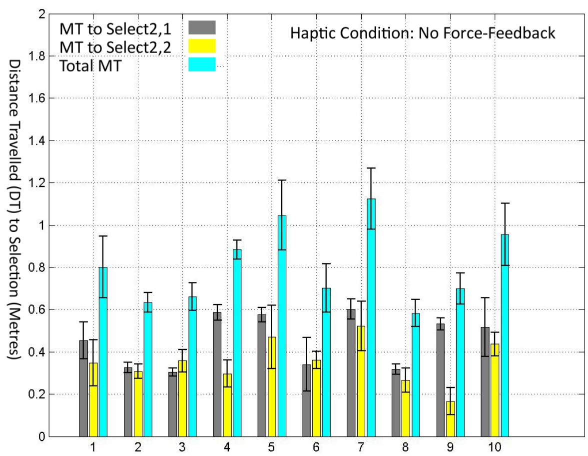
Figure 6.27: Selection of two large targets (SelectLL), Average MT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

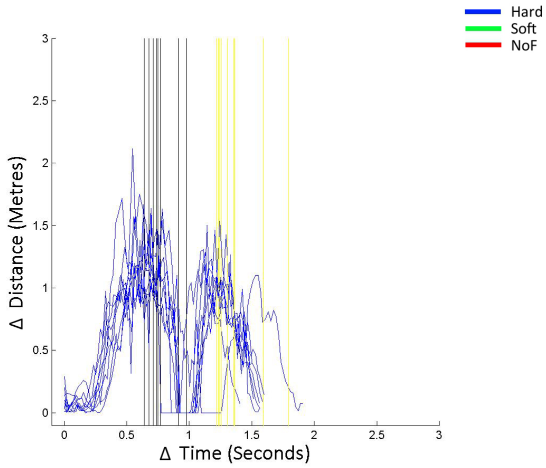


(b) Soft haptic condition

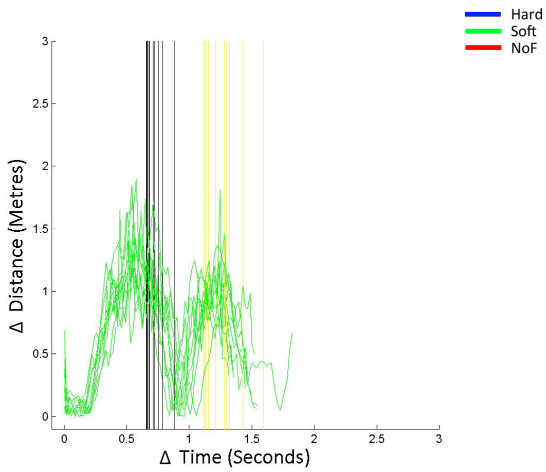


(c) NoF haptic condition

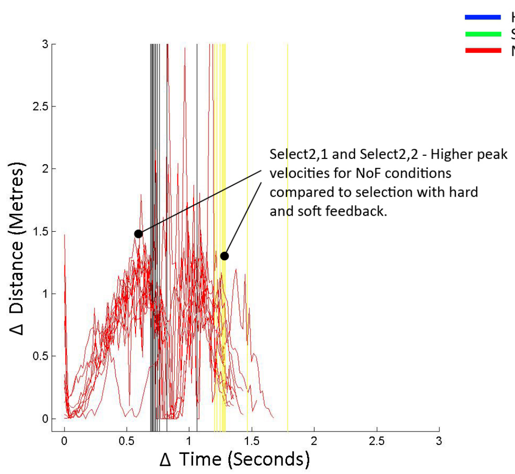
Figure 6.28: Selection of two large targets (SelectLL), Average DT to task completion under hard, soft and NoF haptic conditions



(a) Hard haptic condition

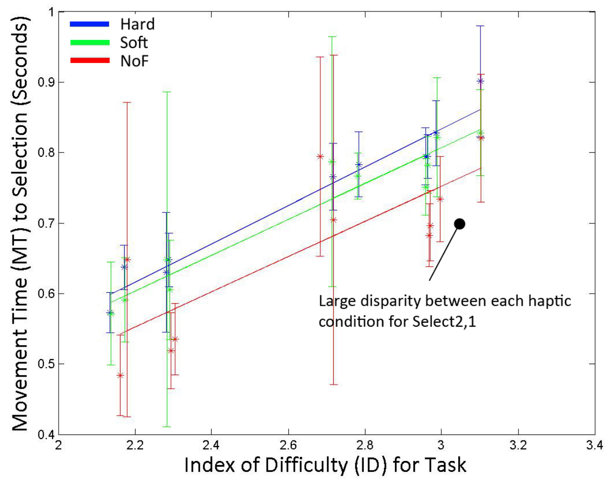


(b) Soft haptic condition

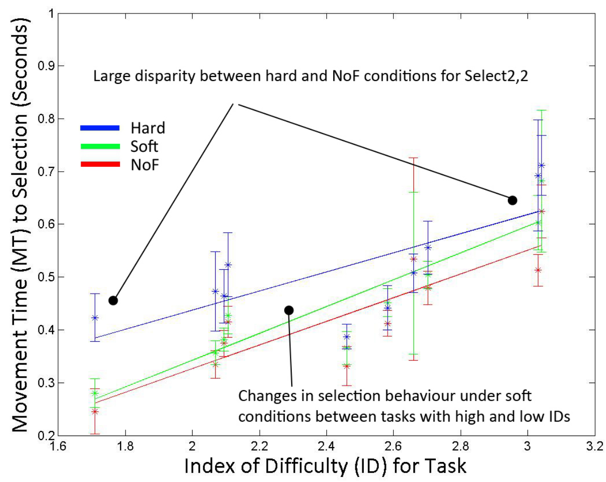


(c) NoF haptic condition

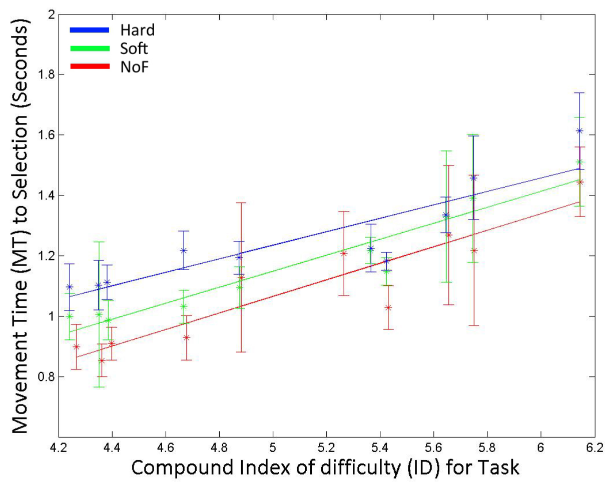
Figure 6.29: Selection of two large targets (SelectLL), Velocity profile for task number 86



(a) Select2,1

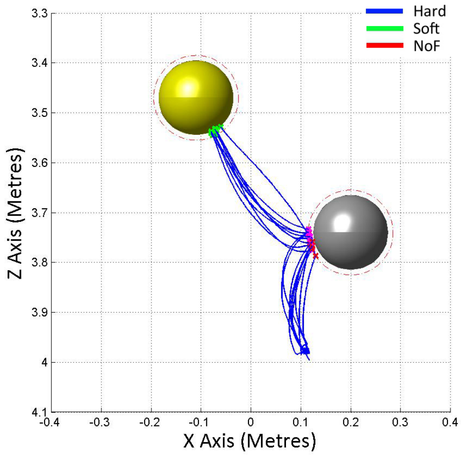


(b) Select2,2

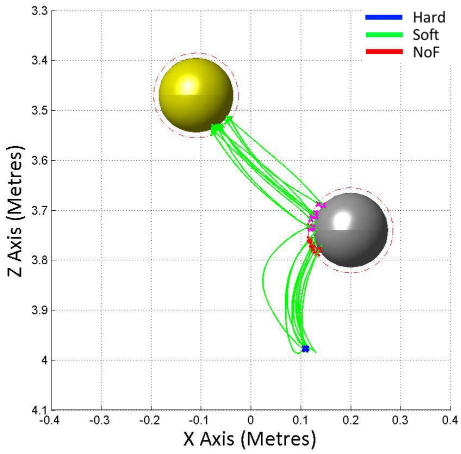


(c) Select2,All

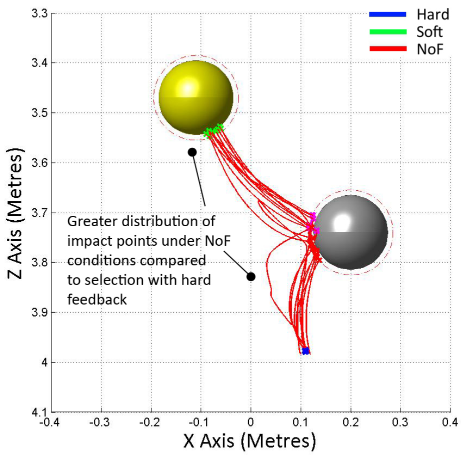
Figure 6.30: Selection of two large targets (SelectLL), MT against ID for each haptic condition



(a) Hard haptic condition



(b) Soft haptic condition



(c) NoF haptic condition

Figure 6.31: Selection of two large targets (SelectLL), Trajectory profile for task number 85

haptic conditions were significantly different to selection with targets that provided soft and no feedback.

DT performance for SelectLL against other target sizes:

SelectLL resulted in variations whereby DT performance was best in comparison to results for the other size combinations. Shown in Table 6.21, for task completion SelectLL with hard and soft targets resulted in better DT against SelectSS and SelectLS. Whilst selection with no feedback cues, SelectLL resulted in better DT performance compared to SelectSS. This is an interesting result, suggest that when selecting large targets this had a negative impact on DT performance.

From the computed a set of ANOVA results, both selection with hard and soft targets the DT result for selectLL was often significantly different to results capture for other size combinations. Shown in Table 6.21, whilst this was apparent in more than 9 tasks when selecting with haptic feedback, when using no feedback conditions the number of observed results was less typically less than 7 tasks. In general, this suggests that NoF conditions reduced the detrimental effect of selecting large targets on DT performance.

6.7.4.3 Velocity Taken (VT)

VT performance between haptic force feedback conditions:

VT to task completion was quickest when selecting targets under NoF conditions. Shown in Table 6.19, the difference in VT to Select2,All under NoF conditions compared to selection with hard and soft feedback was on average slower by 0.186m/s and 0.128m/s respectively. The difference in VT between hard and soft conditions, participants selected soft targets faster by 0.058m/s. For both hard and soft haptic conditions the difference in DT compared to selection without feedback was greater than 3 standard deviations. For differences between hard and soft conditions this was greater than 1 standard deviation. This showed that for task completion selecting targets with no feedback achieved the best VT results.

By assessing the individual sub-tasks, the biggest disparity between haptic conditions occurred when moving to select the second target. Shown in Table 6.19, VT to Select2,2 under NoF conditions compared to selection with hard and soft was faster by 0.288m/s and 0.168m/s respectively. For Select2,1, the same comparison between selection with and without haptic feedback was half the size. This trend was also evident for differences between hard and soft feedback conditions. With respect to the standard deviation results, differences in VT between selection with and without haptic feedback were greater than 1 standard deviation. For Select2,2 this increased to over 2 standard deviations, including comparisons between hard and soft feedback conditions. This is an interesting result suggesting different VT behaviours when selecting a second large target depending on haptic condition type.

Confirming this trend, from the ANOVA results we found a clear difference in VT performance depending on haptic condition. Shown in Table 6.19, for VT to task completion under NoF conditions compared to selection with hard and soft responses we recorded 9 and 7 tasks with p values less than 0.05 respectively. We also captured 5 tasks where the difference in VT when selecting soft targets was better than under hard haptic conditions. These differences in VT were also evident for Select2,1 and

Table 6.23: Summary of significant results between haptic conditions and changes in size of two target ('x' indicates conditions with significant differences between haptic conditions)

	SelectSS								
	MT			DT			VT		
	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A	Sel2,1	Sel2,2	Sel2,A
Hard vs NoF							x		x
Hard vs Soft									
Soft vs NoF									
	SelectSL								
Hard vs NoF	x			x	x	x	x	x	x
Hard vs Soft					x	x			
Soft vs NoF				x	x	x	x	x	x
	SelectLS								
Hard vs NoF							x		x
Hard vs Soft									
Soft vs NoF							x		x
	SelectLS								
Hard vs NoF	x	x	x		x	x	x	x	x
Hard vs Soft									
Soft vs NoF							x		x

Select2,2. Therefore, this demonstrates that haptic feedback condition affects VT performance when selecting two large targets and its sub-tasks.

Based upon the velocity profiles, we can see differences between Select2,1 and Select2,2 between selection with and without haptic feedback. Interestingly, as shown in Figure 6.29, the peak velocities for Select2,1 were larger under hard and soft conditions compared to selection without haptic feedback. However, for Select2,2, selection under NoF conditions achieved the highest peak velocities. Interestingly, for hard and soft feedback conditions, there are sharper deceleration curves upon and before selection of both targets. As a result, under NoF conditions participants were able to carry more speed throughout the selection of both targets.

VT performance for SelectLL against other target size:

For SelectLL, VT performance was greater to task completion in comparison to most other size combinations. Shown in Table 6.22, VT to task completion was better except for comparisons to SelectSM, SelectSL and SelectML consistent for all haptic conditions. From Table 6.22 the biggest disparity was recorded against SelectLS whilst the other comparisons were less than 1 standard deviation. These results showed that selecting two large targets is beneficial to VT performance.

From the ANOVA results, VT performance for SelectLL was different to other size combinations. Summarised in Table 6.22, for the majority of comparisons we recorded more than 5 tasks where the VT performance was significantly different between size comparisons. In general these results suggest that selecting large sized targets had a negative impact on VT performance.

6.7.4.4 Trajectory Analysis

By analysing the trajectory profiles, we can see differences in behaviour between haptic conditions. As shown in Figure 6.31, we can see variations in the trajectory in particular on the impact points on the first target and sub movement to the second target. For soft and no feedback conditions, the impact points were more spread across the targets surface compared to those achieved under hard feedback responses. Furthermore, we can see variations in the trajectory of movement from the first target to the second between haptic conditions. Whilst under hard and soft conditions, the movements are more compact, this is not the case under no feedback conditions. Furthermore, movements under no feedback conditions were flatter whilst under hard and soft conditions were arched suggesting movements away from an optimum path.

6.7.5 Discussion

We observed a trade-off in performance between haptic feedback conditions, the number of targets and their size combinations. As found that when selecting a single target, acquiring two large targets with haptic feedback had a detrimental effect to selection performance. In combination with a small target, participants preferred selecting a large target first to then move onto a smaller second target. This suggests that movement between targets was also dependent on the size of the first target. We also found that target size had a significant effect on the acceleration and deceleration curves when moving to and from selecting a target. To summarise these effects we defined the following performance profiles:

Selection of two small targets:

Table 6.24: Selection of two small targets (SelectSS), Summary of results

Performance Marker	Result
MT	- Different haptic conditions had no effect on MT to task completion. - For the sub-tasks, we found small changes in MT between haptic conditions. When moving to the second target, the difference in MT between hard and no force feedback conditions was greater than that observed when moving to select the first target.
DT	- Best DT performance achieved when selecting targets providing hard and soft feedback. Nevertheless, there was no difference in DT performance between hard and soft force feedback conditions. - For the sub-tasks, under NoF conditions longer DT to Select2,1 than Select2,2. For both hard and soft feedback conditions, there was no significant difference in the DT taken to Select2,1 and Select2,2.
VT	No significant difference in VT performance between haptic conditions. - Higher peak velocities achieved for Select2,1 under no force feedback conditions.
SelectSS vs other target	- Against all other size combinations, SelectSS led to the worst MT results. The biggest disparity occurred at Select2,1 against SelectLS and SelectLL. Better MT performance when moving from a larger first object to a small second in comparison to Select2,2 for SelectSS. - Largest DT to task completion for SelectSS in comparison to other size combinations. Disparity in DT between SelectSS and other size combinations similar for hard and soft force feedback conditions. In contrast, for no force feedback conditions this difference in DT was less. Biggest disparity in DT for SelectSS against other size combinations occurred at Select2,1. - SelectSS achieve slower VT results in comparison to selection with the other size combinations and evident for all haptic conditions assessed. Select2,1 achieved higher VT results than Select2,2. - Quicker VT performances for SelectSS at Select2,1 in comparison to SelectSL under both hard and soft force feedback conditions.

As observed when selecting a single small target, we found no difference in the time taken to select both targets between all haptic conditions. Nevertheless, the trade-off between velocity and distance travelled was the same, whereby participants took shorter paths to task completion but at slower speeds when selecting two small targets with haptic feedback. Indicated by the trajectory graphs, with haptic feedback participants were able to select the surface of both targets without taking extra movements to confirm the selection. However, with the presence of a physical feedback response upon contact the speed of movement between targets was slower compared to selection without haptic feedback. As there was no difference in MT, when selecting two small targets it suggests that the extra VT when selecting targets with no feedback negated the benefit of shorter distances taken to task completion under haptic feedback conditions.

Compared to the other target size combinations, SelectSS resulted in larger MT to task completion.

This was also shown for DT and VT, and for all three haptic feedback conditions. In particular, from the speed and distance trade-off, participants took extra DT to select the small first target. This indicated that selecting a small first target has a detrimental effect on performance of the whole task. With respect to the Fitts' law data, this provided poor estimates to the captured data for both Select2,1 and Select2,2.

Selection of a small then large target:

Table 6.25: Selection of small then large target (SelectSL), Summary of results

Performance Marker	Result
MT	- MT performance was best under no force feedback conditions. Hard force feedback conditions achieved the worst MT results. - Noticeable difference between hard and soft feedback conditions, whereby for Select2,2 MT was less when selecting a large second target that provided soft responses upon contact.
DT	- DT performance to task completion was best when selecting targets that exerted hard and soft force feedback upon contact. The difference between both hard and soft conditions compared to selection with no feedback was greater than 1 standard deviation. - For Select2,1, large difference in performance between selection with both hard and soft haptic conditions compared to selection with no force feedback.
VT	- VT performance to task completion was best under NoF haptic conditions. Hard force feedback conditions led to worst VT results.
SelectSL vs other target size combinations	- MT for SelectSL was larger compared to SelectLL to task completion. - MT for Select2,1 under SelectSL was slower against to all other size combinations. - For SelectSL, DT performance with respect to the other size combinations varied with haptic feedback condition. For hard feedback conditions DT performance for SelectSL was worse against the majority of size combinations except SelectSS. For Soft and no feedback, DT performance for SelectSL was often better to task completion against other size combinations especially for Select2,2. - Under hard and soft feedback conditions slower VT results recorded for SelectSL against other size combinations. Conversely, under no feedback condition VT results were better for SelectSL against other size combinations. -In contrast to SelectLS and SelectLL, participants selected the first target with a greater velocity.

Participants performed best without haptic feedback when selecting a small then large target. Whilst, the size of the path taken to task completion was shorter with hard and soft feedback, the speed of movement was much quicker when selecting the two targets without haptic feedback. In particular, when moving to select the second large target, the difference between each haptic condition for MT and VT was at its greatest. This is an interesting result, suggesting that whilst haptic feedback improved the distance taken to select a target, there is a negative effect on VT when selecting a large target with hindered the overall performance.

Compared to the other size combinations, selecting a small then large target did not led to better results except against SelectSS. This was evident for both soft and hard feedback conditions. However, when selecting targets without haptic feedback, participants were able to select both targets at a greater speed. In contrast to SelectLS and SelectLL, participants selected the first target with a greater velocity for all haptic conditions. This suggests that target size and its order has an affect on overall performance to task completion.

The Fitts' law data achieved poor estimates for Select2,1. For Select2,2 selection with hard feedback led to the best correlations. Again this shows that the size and distance characteristics when selecting a large target can be modelled by Fitts' law.

Selection of large then small target:

Table 6.26: Selection of large then small target (SelectLS), Summary of results

Performance Marker	Result
MT	- To task completion, we found no significant differences in MT between hard, soft and NoF haptics conditions. - For Select2,1 there was a difference in MT between selection with and without haptic feedback.
DT	- Under hard and soft feedback conditions, participants selected both targets with the shortest path. NoF conditions led to longer DT results for task completion and sub-tasks. - For comparisons between soft and hard feedback results, for select2,1 we found no difference in DT performance.
VT	VT performance using haptic feedback was best selecting targets with no feedback. When using hard and soft feedback conditions, VT performance was slower to task completion with significant differences between haptic conditions when moving to the second target. From the velocity profiles, we noticed distinctions in peak velocity and deceleration upon selection between sub-tasks and haptic conditions.
SelectLS vs other target size combinations	- SelectLS achieved better MT results compared to SelectSS and SelectSL. This trend did not continue for Select2,2. - With respect to the effect of target size on DT performance, we noticed variations in the performance profiles for each of the three haptic conditions. - When comparing selectLS to the other size combinations, VT performance when selecting both large and small targets was worse.

There was no difference in time taken to task completion between haptic conditions. Whilst selection without haptic feedback led to longer paths being taken, the speed of movement was greater. In particular, when selecting a large first target, we found no difference in DT between the haptic conditions. Unlike SelectSL, selecting a large first target overcame the need to take extra movements to select the target. However, moving to select a second small target was detrimental to performance.

Selection performance for SelectLS was better than selecting a small first target. However, selecting a smaller second target resulted in poor overall results. In particular, the speed of movement profile over the two targets was worse compared to selection with the other size combinations. In addition, a Fitts' law model did not provide good estimates for both Select2,1 and Select2,2. This indicates that selecting a large first target affects performance when moving to the second target.

Selection of two large targets:

Table 6.27: Selection of two large targets (SelectLL), Summary of results

Performance Marker	Result
MT	Best MT results were achieved under NoF haptic conditions to task completion and sub-tasks.
DT	DT to task completion was best under hard haptic conditions.
VT	Participants selected with the highest average velocity under no feedback conditions. By evaluating the velocity profiles further, we noticed that under no feedback conditions, participants are able to maintain a higher peak velocities in addition to accelerations between objects.
SelectLL vs other target size combinations	- For selection under soft and no feedback results, SelectLL produced better MT results in comparison to all other size combinations. For selection with hard targets, MT performance was only better against size combinations SelectSS and SelectSL. - Between all three haptic conditions, DT performance for SelectLL compared to the other size combinations varied. - With selectLL, participants selected with least velocity compared to the other size combinations.

The time taken to task completion was best under no haptic conditions. Whilst the path taken to both targets was shorter with haptic feedback, the speed of movement was much greater without haptic feedback. In particular, participants were able to maintain their VT over the two targets better. Again, this suggests that whilst haptic feedback improves the efficiency of the path taken, the detrimental effect on VT negates this benefit. Ultimately, with the increase in target size thus reducing the difficulty of the task, selection without haptic feedback resulted in the best performing condition limiting the need to extra DT when selecting the surface of the targets.

Interestingly, compared to the other size combinations, VT performance was the worst. This suggests that size also had an effect on VT. Therefore, this shows that there is an optimum size of targets to achieve the best ratio between distance and velocity characteristics. With respect to the Fitts' law model, this provided good estimates when selecting targets with haptic feedback. Similar to SelectL, this shows that a Fitts' law can be used to model selection of large targets.

From the profiles shown in Tables 6.24, 6.25, 6.26 and 6.27, we found that MT, DT and VT performance changed with haptic feedback, target size and their combinations. In broad terms, we observed similar results to the Select1, whereby DT improved with haptic feedback. However, increases in target size led to slower VT results. In particular, whilst selecting small targets did not led to significant differences in performance between haptic conditions, for larger size combinations we found changes in the impact points to the first target and the subsequent trajectories taken to complete the task. By providing soft or hard haptic responses, having to select a large target hindered performance by making participants take a longer path around objects rather than being able to push through.

Furthermore, based upon the velocity profiles these results also demonstrate the trade-off between haptic feedback and task efficiency. In particular, when selecting a large target with hard haptic feedback, the rate of acceleration and deceleration was much slower compared to selection under either soft and NoF conditions negating the benefit of selecting a larger target. Furthermore, these results also showed that the movement for between targets was different for each haptic condition and size combination whereby selecting large targets results in slower movement speeds between targets.

For comparisons between selection of a single and multiple targets, we observed different task performances with respect to each haptic condition, including changes in task efficiency when moving from the first and onto the second target. By comparing these results to Fitts law, our findings show that 3D selection is much more complex than being defined by target size and displacement.

To summarise, these results indicate that:

- No difference in performance between haptic conditions when selecting two small targets.
- Hard haptic conditions had a significant detrimental effect of VT and DT performance when selecting two large targets.
- Participants achieved better results when selecting a large then smaller target.
- Large targets have a negative impact on DT as participants have to move around hard targets and results in slower movement speeds to touch and moving away from the another target.
- Other factor such as the impact/exit points, number of targets, size and haptic feedback response play a role in task performance.

6.8 Summary

In this chapter we discussed the trade-off between haptic feedback and target size on task efficiency. Specifically, we found that haptic feedback has a detrimental effect on the acceleration and deceleration patterns when moving to select a target negating the benefit of having a larger area to touch. By performing a set of Fitts' law estimates, we also noticed that moving to the first target of two is poorly defined. This is also true when selecting small targets suggesting this is a limiting factor to the effects of haptic feedback on task efficiency. These results provide substansive information that 3D selection in IVE requires further consideration. In particular, if we want to include haptic feedback, target size and the number of targets greater influences the user selection strategies.

Chapter 7

Conclusions

The main contribution of this thesis is a set of studies exploring the effect of haptic feedback on 3D selection using distal and natural interaction techniques. To do so, we first developed a hardware setup and experimental framework suitable for the evaluation of different interaction techniques within a common IVE domain. This involved achieving the following tasks:

- *Developed methods to integrate two large scale haptic devices within a CAVE^{TM}-like IVE display system*- This involved defining the fundamental characteristics of the GRAB device and ReaCToR projection system to then select a suitable visualisation platform for the concurrent display of visual and haptic cues. More specifically, we created a network whereby different types of tracking, haptic and visual display units could be synchronised and controlled within the XVR platform.

- *Developed calibration protocols mapping the local coordinate frames of the connected display and tracking devices to a global temporal and spatial frame*- We mapped the spatial resolution and distortion of the GRAB and UCL ReaCToR display systems. By doing so, we established the correspondence between the movements made by the haptic device and visual changes in the IVE. This enabled us to measure the accuracy of the hardware setup, and in turn limit the effects of any distracting factors caused by visual-haptic misalignment or crosstalk.

- *Co-location of visual and haptic cues within a CAVE^{TM}-like IVE*- Based upon the developed calibration protocols, we co-located the visual and haptic cues generated from the GRAB arms and UCL ReaCToR display devices. We also evaluated the accuracy of these methods and proposed methods to optimise the output.

- *Presentation of a testbed evaluation framework for assessing 3D selection performance*- To define a suitable evaluation framework to assess the performance of different 3D interaction techniques, we trialled a set of different experiment designs based upon the literature. We chose a testbed design as this lent well to developing a set of experiments that were highly repeatable. We also evaluated different types of interaction tasks suitable for our evaluations and hardware setup, narrowing this down to a set of 3D selection tasks involving single and multiple targets.

- *Implementation of distal and natural interaction techniques for 3D selection*- We presented a set of methods implementing a go-go hand, velocity based travel and natural interaction technique tailored for the available equipment. To establish these parameters we used pilot studies with expert users.

- *Logging and analysis tools suitable for evaluating user performance of 3D selection tasks*- To prevent any interference between the write loop that captured the performance data and the IVE simulation, we developed a set of low latency logging functions. Due to the size of these log files, we also created a number of MATLAB scripts to analyse the multimodal data sets.

The above tasks represent a set of minor contributions that enabled the evaluation of different interaction techniques on 3D selection. Based on this setup, we designed three user studies by building upon the results from each other. We discussed these findings in three parts:

Chapter 4- Haptic Force Feedback Effects on Distal 3D Selection:
We started by studying the effects of haptic feedback when using distal interaction techniques. More specifically, we evaluated two types of distal interaction techniques commonly used within large scale IVEs: arm extension and velocity based travel. Being the first experiment conducted in this thesis, we used the results to highlight the different variables that affected selection performance with and without force feedback. Besides informing the design of future experiments conducted in chapters 5 and 6, it also helped reduce the scope and target variables of interest such as target size, number and combination.

For each interaction technique (arm extension and velocity based travel) we evaluated 40 participants, 20 for each haptic force feedback conditions. For each trial, each participant selected targets for both selection techniques but with only one haptic condition. We evaluated performance based upon selecting a single or two targets placed at different displacements away from the participant. The capture data was then used to provide comparisons in selection behaviour with and without haptic feedback.

By evaluating these interaction techniques when selecting targets with and without force feedback, the captured results highlighted different movement behaviours dependent on haptic condition. When moving to select a single target, we found that haptic feedback did not affect user performance. In contrast, selection when multiple targets led a trade-off in task efficiency whereby participants had to take longer paths by moving around objects that provided a physical resistance; leading to more effort being made to complete the task. Interestingly, as the complexity of the interaction technique and selection task came difficult to perform, haptic feedback was also used to overcome control limitations such as providing physical reference points when selecting targets with a large displacement. For selection with velocity based travel techniques, we found similar differences with respect to haptic feedback and selection of a single and multiple targets. Altogether, the main results of this study were:

- Results for single object selection with haptic feedback did not transfer when asked to select multiple targets.

- Haptic feedback was detrimental to user performance when selecting multiple targets.

- For instances whereby the interaction technique was hard to control, haptic feedback provided a benefit to user performance and enable participants to use gestures in novel ways to overcome these limitations.

With respect to the design of distal interactions, these results can be used to describe when and when not to use haptic feedback to improve 3D selection. The experiments also provide insights to the use of different control gains when traversing large scale IVEs and their 3D performance with and without haptic feedback.

Chapter 5- Haptic Force Feedback Effects on Natural 3D Selection:
In this study we developed a natural selection technique by co-locating the visual and haptic display devices to a common spatial and temporal domain. With this setup we investigated the effect of haptic feedback on 3D selection with right and two handed interaction. Building upon results from chapter 4, the presented experiments represent a more focused attempt to explore the effects to 3D selection when asked to target objects with three different types of haptic force feedback responses. By doing so, we were able to evaluate the effect of selecting multiple targets and changes to their surface stiffness.

In total we evaluated 45 participants, 15 for each of the three haptic conditions. A real-time logging system was developed to capture the data to then plot velocity and trajectory graphs. From this, we able to analyse the type of gestures used to select targets under different haptic force feedback conditions.

The results highlighted that participants took different movement patterns taken for each haptic condition when asked to select multiple targets. More specifically, these were represented by changes with respect to MT, DT and VT, in addition to the impact points and behaviour on the surface of targets when manoeuvring either hand to complete tasks. When selecting a single target, we found no difference between haptic feedback conditions. In contrast, when selecting multiple targets selection with hard and soft feedback improved DT performance in particular the task efficiency when selecting target surfaces to move between objects, thus improving overall performance. However, VT performance was best under NoF conditions as participants were able to retain their velocity and not stop upon selection with a target. This is an interesting result which shows a trade-off in DT and VT that is also dependent on the number of targets to select and the type of haptic feedback felt upon contact.

With respect to selection using bi-manual interaction, we found that this reduced the difficulty of the task. As participants were able to use both hands in cooperation, this reduced the complexity of the task. For example, Select3 was reduced to movements similar to either selecting one target with the right hand and two targets with the left hand. Similar to selection with the right hand only, haptic feedback improved performance for Select3. For Select1 and Select2, we found no difference in performance between haptic feedback conditions.

To summarise, the main results were:

- Results for single object selection were significantly different to the strategies used when selecting multiple targets.
- Hard and soft haptic feedback improved the accuracy of the impacts made on the surface of targets and in turn shortened subsequent trajectory taken to task completion.

- Soft feedback responses led to the best selection results for multiple target selection.
- Under hard conditions, the speed of movement was reduced. Participants had to put in more effort decelerating and accelerating between targets.
- NoF conditions led to difficulties selecting suitable impact points on the surface of targets to make efficient subsequent movements to task completion. However, participants were able to move with greater speed between targets.
- Bi-manual interaction enabled participants to reduce the difficulty of selecting multiple targets. For example, when selecting 3 targets, this could be segmented into the right hand targeting two objects whilst the left hand selected the final object.

These results give a detailed analyse of the effects of haptic feedback on 3D selection. From the trajectory and velocity profiles, the experiments in this chapter provide information on the gestures and movement behaviours when targeting single and multiple objects. By using this information, we can begin to discuss the utility of haptic force feedback. In particular, we can show that there are instances whereby different types of haptic feedback can hinder but also help selection performance.

Chapter 6- Effect of Target Size and Haptic Force Feedback on Natural 3D Selection:
Based upon results in chapter 5, we developed an experiment to provide a 'deeper dive' into the other factors that affect 3D selection. Specifically, we investigated the role of target size with respect to haptic feedback. We also compared the captured results to Fitts' law.

We collected data from 30 participants, each performing a set of selections tasks for one force feedback condition only. Similar to chapter 5, we presented a set of targets that varied in small and large sizes. We also investigated selection behaviour when targeting one and two objects, in addition to their combination.

We found that increases in target size had a detrimental effect on performance when selecting targets with haptic feedback. Interestingly, the results captured when selecting large sized targets with haptic feedback contradicted the information theory perspective that bigger objects should result in better selection performance. For this case, hard haptic responses resulted in participants putting in more effort by having to move around objects that provided a physical response, in addition to reducing their acceleration and deceleration profiles when moving between targets. By also comparing these results to a Fitts' law, the results suggest that there are limitations to this model with respect to multiple target selection, target of a small size and haptic feedback response. The main results of this study were:

- No difference in performance between haptic conditions when selecting a small target
- Hard haptic response when selecting large multiple targets had a detrimental effect on the speed of movement in addition to the size of paths taken to selection.
- NoF conditions achieved better results when selecting large targets.

- Fitts' law did not provide a good model to the selection between multiple targets with different size combinations, in addition to the effects of haptic feedback. Nevertheless, good estimates were recorded when selecting large targets.

The results captured in this chapter demonstrate the interaction between haptic feedback, target size and their combination on selection performance. In particular, whilst selecting small targets did not lead to significant differences in performance between haptic conditions, for larger size combinations we found changes in the impact points to the first target and the subsequent trajectories taken to complete the task. For comparisons between selection of a single and multiple targets, we observed different task performances with respect to each haptic condition, including changes in the movement from the first and onto the second target. By comparing these results to Fitts' law, our findings show that 3D selection is much more complex than being defined by target size and displacement. Other factor such as the impact/exit points, number of targets, size and haptic feedback response play a role in task performance.

Altogether, the results presented are significant, suggesting that the utility of haptic force feedback is not uniform and competes with other factors that define 3D selection performance.

7.1 Future Work

The results of this thesis highlighted the complexity in defining 3D selection performance. As identified in chapters 4, 5 and 6, there are a broad range of factors to consider that effect how users select targets beyond the difficulty of the task already evaluated. The interactions of these factors with respect to haptic force feedback are each individual areas for future exploration. For example, this includes understanding the effect of object rotation, shape, appearance etc. In total, this provides a large list of potential smaller user studies to be performed. When put altogether, these studies will provide enough data for building a 3D selection model that includes the effects of haptic force feedback. In particular, we would like to extend Fitts' law into the 3D domain. By doing so, this would provide designers of 3D user interfaces a framework to understand the trade-offs in interaction performance to a set of well-defined variables.

By extending the studies in this thesis, this will also provide an opportunity to overcome known limitations. Specifically, we would like to validate the results with different types of haptic devices. This would give us information on device specific variables such as the effect of transparency on 3D interaction performance which is useful to the design of haptic interfaces. Expanding the sample size and demographic is also another area to improve upon. For example, we noted posture had effect on the types of trajectories participants took to task completion. Therefore, by explicitly measuring these aspects in future studies we will be able to link the captured performance results to the biomechanics of the participant.

Beyond 3D selection, investigating manipulation tasks is another future direction. In terms of scope, this research area is much bigger compared to defining 3D selection performance. For example, additional factors such object surface properties are thought to be important to user manipulation performance. However, potential constraints include the need for extra hardware components to assess these factors properly, in addition to the evaluation frameworks themselves. Other parameters worth considering would be object deformation and manipulation tasks that involve changes in stiffness such as those commonly found in medical and dental scenarios. We believe this type of work will help develop a framework for assessing 3D skills. For applications such as medical surgical training, being able to quantify skill would provide assessors an opportunity to change current teaching paradigms. Equally, this type of work could be used as a validation tool to maintain skill competency.

Another area of research would be to understand how best to utilise haptic force feedback to improve interaction techniques within IVEs. For these studies, haptic feedback could be used in novel ways intended to assist the user. In particular, this builds upon work related to gravity wells and other rehabilitation examples that use haptic feedback to guide the user and overcome difficulties in the presented task. An extension to this would include the use of EMG scanner to link the interactions performed the user to activity in their brain. Haptic illusions could also be tested to see how changes in visual and haptic feedback are linked to the CNS. We expect results from modelling 3D selection and manipulation tasks to be informative, as it will provide insights to how haptic feedback affects task efficiency.

The developed experiments and data logging systems provided a framework for analysing human hand motions and skills within multimodal environments. As a starting point, we can quickly run more focused experiments, and overcome limitations with those presented in this thesis. We can also capture a large sample size with greater variations in demographic. Other types of haptic interfaces and interaction tasks can also be evaluated. Alternatively, we can use this data capture system in other 3D user interfaces such as mirror display to evaluate small scale interactions. By doing so, we can evaluate the effects of difference designs of 3D interfaces such as the impact on posture and the resultant interaction behaviour.

The design of natural 3D user interfaces could also benefit from the developed experiments and analysis systems. These could be used to evaluate the effect of individual hardware components and configurations on 3D interaction performance. Again, for scenarios such as virtual reality medical trainers, being able to identify how different hardware configurations affect the user is important to establishing their efficacy. Furthermore, it will help designers understand what are the permissible device level characteristics such as transparency of the haptic device, stiffness response and workspace limitations. This information will also be useful in building natural 3D user interfaces for tele-operation systems that requires real time input.

7.2 Publications

The following publications, all appearing in peer-reviewed international conferences. They are presented in chronological order according to date of publication.

Vijay M. Pawar and Anthony Steed, Evaluating the Influence of Haptic Force-Feedback on 3D Selection Tasks using Natural Egocentric Gestures, IEEE VR 2009, pages 11-18

Vijay M. Pawar and Anthony Steed, Profiling the behaviour of 3D selection tasks on movement time when using natural haptic pointing gestures, IEEE VRST 2009, pages 79-82

All code is presented in the attached CD. The directory list is segmented into labels: 'Appendix A', 'Appendix B' and 'Appendix C'. The graphs and other plots are included in these directories.

.1 Appendix A

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Department of Computer Science
Vijay Pawar

Trial ID:
PROJECT: Haptic Feedback on 3D Interaction in IVEs
Investigators: Vijay Pawar, Anthony Steed

To be completed by volunteers:
We would like you to read the following questions carefully.

Have you read the information sheet about this study?	YES/NO
Have you had an opportunity to ask questions and discuss this study?	YES/NO
Have you received satisfactory answers to all your questions?	YES/NO
Have you received enough information about this study?	YES/NO
Do you understand that you are free to withdraw from this study?	
• At any time	YES/NO
• Without giving a reason for withdrawing	YES/NO
Do you understand and accept the risks associated with the use of virtual reality equipment?	YES/NO
Do you agree to take part in this study?	YES/NO
Do you agree to be videotaped?	YES/NO
Do you agree to have your head and body motions tracked?	YES/NO

I certify that I do not have epilepsy.
I certify that I will not be driving a car, motorcycle, bicycle, or use other types of complex machinery that could be a danger to myself or others, within 3 hours after the termination of the study.

Signed.......................................Date.................................
Name in block letters...
Investigator..

In case you have any enquiries regarding this study in the future, please contact:

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Figure 1: Consent form used for experiments in chapters 4, 5 and 6

LONDON'S GLOBAL UNIVERSITY

UCL

INFORMATION SHEET FOR PARTICIPANTS

Thank you for participating in our study. This is series of studies into understanding 3D interaction within Immersive Virtual Environments (IVEs). This study has been approved by *University College London's Committee on the Ethics of Non-NHS Human Research*. Please read through this information sheet and feel free to ask any questions. The experimenters will answer any general questions; however the specific aspects regarding this study cannot be discussed with you until the end of the session. The whole study will take about *least than one hour*.

You will be using the CAVE-like system called the ReaCToR. See figure below.

The ReaCToR is a VR system made up of 3 walls measuring roughly 3m x 3m x 3m. You will wear VR glasses, a tracker and a haptic interface to perform interactions within the IVE. The virtual reality viewing equipment can be worn over eyeglasses. You may be asked to take off your shoes in order to protect the virtual reality equipment.

In this particular study you will be going into a party by yourself and there are a few other people there. Some of them may talk to you, and you can talk with them if you wish. We the experimenters will not be there with you.

PLEASE TURN OVER

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Figure 2: Participation form used for experiments in chapters 4, 5 and 6

C.1. Information Sheet for Participants ....

Please ask any questions that come to mind. Read and sign the **Consent Form**.

Information that we collect will never be reported in a way that specific individuals can be identified. Information will be reported in a statistical and aggregated manner, and any verbal comments that you make, if written about in subsequent papers, will be presented anonymously.

IMPORTANT

When people use virtual reality systems, some people sometimes experience some degree of nausea. If at any time you wish to stop taking part in the study due to this or any other reason, please just say so and we will stop.

There has been some research, which suggests that people using head-mounted displays might experience some disturbances in vision afterwards. No long term studies are known to us, but the studies which have been carried out do testing after about 30 minutes, and find the effect is still sometimes there. There have been various reported side effects of using virtual reality equipment, such as 'flashbacks'.

With any type of video equipment there is a possibility that an epileptic episode may be generated. This, for example, has been reported for computer video games.

PROCEDURES

- You will be asked to read, understand and sign a **Consent Form**. If you sign it the study will continue with your participation. **Note that you can withdraw at any time without giving any reasons.**
- You will be asked to complete a number of questions on paper, so that we can try to understand your responses during the study.
- You may be asked to remove your shoes and switch off mobile phones before using the VR equipment.
- You will have a training period standing in the CAVE and understand how to use the equipment available to this study. You will then go into the environment as mentioned above and stay there for a few minutes during which you will be videotaped.
- After the visit to the environment you will complete a questionnaire about your experience, and a questionnaire which is similar to the one you did before coming.
- Finally there will be a small discussion with the experimenters about your experiences.
- During this time, you might be audio or video taped.

Thank you for your participation. Please do not discuss this study with others for about **three months**, since the study is continuing.

Any other questions?

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Figure 3: Participation form used for experiments in chapters 4, 5 and 6

ID: _____________ Background Questionnaire:

Questions:	***Please tick the appropriate box where relevant***
Your age:	
Your height:	
How fluent is your English?	Basic □ Proficient □ Fluent □
Occupational status *(If other, please specify and also your area of interest)*	Undergraduate Student □ Masters Student □ PhD Student □ Research Assistant/Fellow □ Staff - systems, technical □ Faculty □ Administrative Staff □ Other □
Please state your level of computer literacy on a scale of (1...7)	(novice) 1 2 3 4 5 6 7 (expert)
Please rate your level of experience with computer *programming on a scale of (1...7)*	(novice) 1 2 3 4 5 6 7 (expert)
Have you ever experienced 'virtual reality' before?	(no experience) 1 2 3 4 5 6 7 (extensive experience)
How many times did you play video games (at home, work, school, or arcades) in the last year?	Never □ 1 - 5 □ 6 - 10 □ 11 - 15 □ 16 - 20 □ 21 - 25 □ > 25 □
How many *hours per week* do you spend playing video games?	0 □ < 1 □ 1 - 3 □ 3 - 5 □ 5 - 7 □ 7 - 9 □ > 9 □

Figure 4: Background questionnaire used for experiments in chapters 4, 5 and 6

ID: _____________ Usability Questionnaire:

Questions:	***Please tick the appropriate box where relevant***
Was the interaction technique easy to use?	(1=Hard to use) 1 2 3 4 5 (5=Easy to use)
Did the interaction feel natural to use?	(1=Not natural) 1 2 3 4 5 (5=Natural)
Was the interaction responsive?	(1=Not responsive) 1 2 3 4 5 (5=Responsive)
Did you feel sick?	(1=Sick) 1 2 3 4 5 (5=Normal)
Did you experience any delay of feedback?	(1=Small) 1 2 3 4 5 (5=Large)
How would you rate the interaction technique?	(1=Bad) 1 2 3 4 5 (5=Good)
How would you rate presented tasks?	(1=Hard) 1 2 3 4 5 (5=Easy)

Figure 5: Usability questionnaire used for experiments in chapter 4

Table 1: Chapter 4, Linear and non-linear arm-extension, Breakdown of participant details

Experiment ID	Participant ID	Prior use of equipment	Gender	Handedness	First technique
HtF_#1	#101	Yes	Male	Right	NL-AE
HtF_#2	#102	Yes	Male	Right	NL-AE
HtF_#3	#103	Yes	Male	Right	L-AE
HtF_#4	#104	Yes	Male	Right	NL-AE
HtF_#5	#105	Yes	Female	Right	L-AE
HtF_#6	#106	No	Male	Right	NL-AE
HtF_#7	#107	No	Male	Right	NL-AE
HtF_#8	#108	No	Male	Right	NL-AE
HtF_#9	#109	No	Male	Right	L-AE
HtF_#10	#110	No	Male	Right	NL-AE
HtF_#11	#111	No	Male	Right	L-AE
HtF_#12	#112	No	Male	Right	L-AE
HtF_#13	#113	No	Male	Right	NL-AE
HtF_#14	#114	No	Male	Right	L-AE
HtF_#15	#115	No	Male	Right	NL-AE
HtF_#16	#116	No	Male	Right	L-AE
HtF_#17	#117	No	Male	Right	NL-AE
HtF_#18	#118	No	Male	Right	L-AE
HtF_#19	#119	No	Male	Right	NL-AE
HtF_#20	#120	No	Male	Right	L-AE
NoF_#1	#201	Yes	Male	Right	L-AE
NoF_#2	#202	Yes	Male	Right	L-AE
NoF_#3	#203	Yes	Female	Right	L-AE
NoF_#4	#204	No	No	Right	NL-AE
NoF_#5	#205	No	No	Right	NL-AE
NoF_#6	#206	No	No	Right	L-AE
NoF_#7	#207	No	No	Right	L-AE
NoF_#8	#208	No	No	Right	L-AE
NoF_#9	#209	No	No	Right	NL-AE
NoF_#10	#210	No	No	Right	NL-AE
NoF_#11	#211	No	No	Right	L-AE
NoF_#12	#212	No	No	Right	L-AE
NoF_#13	#213	No	No	Right	L-AE
NoF_#14	#214	No	No	Right	L-AE
NoF_#15	#215	No	Female	Right	L-AE
NoF_#16	#216	No	No	Right	NL-AE
NoF_#17	#217	No	No	Right	NL-AE
NoF_#18	#218	No	No	Right	NL-AE
NoF_#19	#219	No	No	Right	NL-AE
NoF_#20	#220	No	No	Right	NL-AE

Simulator Sickness Questionnaire:

Please fill in the questionnaire below by putting circle around the most appropriate answer:

1.	General discomfort	None	Slight	Moderate	Severe	
2.	Fatigue	None	Slight	Moderate	Severe	
3.	Boredom	None	Slight	Moderate	Severe	
4.	Drowsiness	None	Slight	Moderate	Severe	
5.	Headache	None	Slight	Moderate	Severe	
6.	Eyestrain	None	Slight	Moderate	Severe	
7.	Difficulty focusing	None	Slight	Moderate	Severe	
8.	Salivation increase	None	Slight	Moderate	Severe	
	Salivation decrease	None	Slight	Moderate	Severe	
9.	Sweating	None	Slight	Moderate	Severe	
10.	Nausea	None	Slight	Moderate	Severe	
11.	Difficulty concentrating	None	Slight	Moderate	Severe	
12.	Mental depression	No	Yes (	Slight	Moderate	Severe)
13.	"Fullness of the head"	No	Yes (	Slight	Moderate	Severe)
14.	Blurred vision	No	Yes (	Slight	Moderate	Severe)
15.	Dizziness eyes open	No	Yes (	Slight	Moderate	Severe)
	Dizziness eyes close	No	Yes (	Slight	Moderate	Severe)
16.	Vertigo	No	Yes (	Slight	Moderate	Severe)
17.	Visual flashbacks*	No	Yes (	Slight	Moderate	Severe)
18.	Faintness	No	Yes (	Slight	Moderate	Severe)
19.	Aware of breathing	No	Yes (	Slight	Moderate	Severe)
20.	Stomach awareness	No	Yes (	Slight	Moderate	Severe)
21.	Loss of appetite	No	Yes (	Slight	Moderate	Severe)
22.	Increased appetite	No	Yes (	Slight	Moderate	Severe)
23.	Desire to move bowels	No	Yes (	Slight	Moderate	Severe)
24.	Confusion	No	Yes (	Slight	Moderate	Severe)
25.	Burping	No	Yes (	Slight	Moderate	Severe)
26.	Vomiting	No	Yes (	Slight	Moderate	Severe)
27.	Other	No	Yes (	Slight	Moderate	Severe)

Figure 6: Simulation Sickness Questionnaire

Table 2: Chapter 4, Linear and non-linear velocity based travel, Breakdown of participant details

Experiment ID	Participant ID	Prior use of equipment	Gender	Handedness	First technique
HtF_#1	#301	Yes	Male	Right	L-VBT
HtF_#2	#302	Yes	Male	Right	L-VBT
HtF_#3	#303	Yes	Male	Right	NL-VBT
HtF_#4	#304	Yes	Male	Right	L-VBT
HtF_#5	#305	Yes	Female	Right	L-VBT
HtF_#6	#306	No	Male	Right	L-VBT
HtF_#7	#307	No	Male	Right	L-VBT
HtF_#8	#308	No	Male	Right	NL-VBT
HtF_#9	#309	No	Female	Right	NL-VBT
HtF_#10	#310	No	Male	Right	L-VBT
HtF_#11	#311	Yes	Male	Right	NL-VBT
HtF_#12	#312	Yes	Male	Right	L-VBT
HtF_#13	#313	Yes	Male	Right	L-VBT
HtF_#14	#314	No	Male	Right	L-VBT
HtF_#15	#315	No	Female	Right	L-VBT
HtF_#16	#316	No	Female	Right	L-VBT
HtF_#17	#317	No	Female	Right	NL-VBT
HtF_#18	#318	No	Male	Right	L-VBT
HtF_#19	#319	No	Male	Right	NL-VBT
HtF_#20	#320	No	Male	Right	NL-VBT
NoF_#1	#401	Yes	Male	Right	NL-VBT
NoF_#2	#402	Yes	Male	Right	NL-VBT
NoF_#3	#403	No	Female	Right	NL-VBT
NoF_#4	#404	Yes	Female	Right	NL-VBT
NoF_#5	#405	Yes	No	Right	NL-VBT
NoF_#6	#406	No	No	Right	NL-VBT
NoF_#7	#407	No	No	Right	L-VBT
NoF_#8	#408	No	No	Right	NL-VBT
NoF_#9	#409	No	No	Right	NL-VBT
NoF_#10	#410	No	No	Right	L-VBT
NoF_#11	#411	No	No	Right	L-VBT
NoF_#12	#412	No	No	Right	L-VBT
NoF_#13	#413	No	No	Right	NL-VBT
NoF_#14	#414	No	Female	Right	L-VBT
NoF_#15	#415	No	Female	Right	L-VBT
NoF_#16	#416	No	No	Right	NL-VBT
NoF_#17	#417	Yes	No	Right	NL-VBT
NoF_#18	#418	Yes	No	Right	L-VBT
NoF_#19	#419	Yes	No	Right	NL-VBT
NoF_#20	#420	Yes	No	Right	NL-VBT

.2 Appendix B

ID: _____________ Usability Questionnaire:

Questions:	***Please tick the appropriate box where relevant***
Was the interaction technique easy to use?	(1=Hard to use) 1 2 3 4 5 6 7(7=Easy to use)
Did the interaction feel natural to use?	(1=Not natural) 1 2 3 4 5 6 7 (7=Natural)
Was the interaction responsive?	(1=Not responsive) 1 2 3 4 5 6 7 (7=Responsive)
Did you feel sick?	(1=Sick) 1 2 3 4 5 6 7(7=Normal)
During the experiment were you aware of the surroundings outside of the CAVE?	(1=Not aware of the outside environment) 1 2 3 4 5 6 7 (7=Very aware of the outside environment)
How would you rate the usability of the interaction technique?	(1=Bad) 1 2 3 4 5 6 7(7=Good)

Figure 7: Usability questionnaire used for experiments in chapter 5

Table 3: Chapter 5, Natural Selection Technique, Breakdown of participant details

Experiment ID P	Participant ID	Prior use of equipment	Gender	Handedness
ex_nof_#1	part_#1	Yes	Female	Right
ex_nof_#2	part_#2	Yes	Male	Right
ex_nof_#3	part_#3	Yes	Male	Right
ex_nof_#4	part_#4	Yes	Male	Right
ex_nof_#5	part_#5	Yes	Male	Right
ex_nof_#6	part_#6	No	Male	Right
ex_nof_#7	part_#7	No	Male	Right
ex_nof_#8	part_#8	No	Male	Right
ex_nof_#9	part_#9	Yes	Male	Right
ex_nof_#10	part_#10	Yes	Male	Right
ex_nof_#11	part_#11	No	Female	Right
ex_nof_#12	part_#12	No	Female	Right
ex_nof_#13	part_#13	No	Female	Right
ex_nof_#14	part_#14	No	Male	Right
ex_nof_#15	part_#15	No	Male	Right
ex_hard_#1	part_#16	Yes	Male	Right
ex_hard_#2	part_#17	Yes	Male	Right
ex_hard_#3	part_#18	Yes	Male	Right
ex_hard_#4	part_#19	Yes	Male	Right
ex_hard_#5	part_#20	No	Male	Right
ex_hard_#6	part_#21	No	Female	Right
ex_hard_#7	part_#22	No	Female	Right
ex_hard_#8	part_#23	No	Female	Right
ex_hard_#9	part_#24	Yes	Male	Right
ex_hard_#10	part_#25	No	Male	Right
ex_hard_#11	part_#26	No	Male	Right
ex_hard_#12	part_#27	No	Male	Right
ex_hard_#13	part_#28	No	Male	Right
ex_hard_#14	part_#29	Yes	Male	Right
ex_hard_#15	part_#30	No	Female	Right
ex_soft_#1	part_#31	No	Female	Right
ex_soft_#2	part_#32	No	Female	Right
ex_soft_#3	part_#33	No	Female	Right
ex_soft_#4	part_#34	No	Male	Right
ex_soft_#5	part_#35	Yes	Male	Right
ex_soft_#6	part_#36	No	Male	Right
ex_soft_#7	part_#37	No	Male	Right
ex_soft_#8	part_#38	Yes	Female	Right
ex_soft_#9	part_#39	Yes	Male	Right
ex_soft_#10	part_#40	Yes	Male	Right
ex_soft_#11	part_#41	Yes	Male	Right
ex_soft_#12	part_#42	No	Male	Right
ex_soft_#13	part_#43	No	Male	Right
ex_soft_#14	part_#44	No	Male	Right
ex_soft_#15	part_#45	No	Male	Right

.3 Appendix C

ID: ______________ Usability Questionnaire:

Questions:	***Please tick the appropriate box where relevant***
Was the interaction technique easy to use?	(1=Hard to use) 1 2 3 4 5 6 7(7=Easy to use)

Figure 8: Usability questionnaire used for experiments in chapter 6

Table 4: Chapter 6, Natural Selection Technique, Breakdown of participant details

Experiment ID P	Participant ID	Prior use of equipment	Gender	Handedness
ex_nof_#1	part_#1	Yes	Male	Right
ex_nof_#2	part_#2	Yes	Male	Right
ex_nof_#3	part_#3	Yes	Male	Right
ex_nof_#4	part_#4	Yes	Male	Right
ex_nof_#5	part_#5	Yes	Male	Right
ex_nof_#6	part_#6	Yes	Male	Right
ex_nof_#7	part_#7	No	Male	Right
ex_nof_#8	part_#8	No	Male	Right
ex_nof_#9	part_#9	No	Male	Right
ex_nof_#10	part_#10	No	Male	Right
ex_hard_#1	part_#11	Yes	Male	Right
ex_hard_#2	part_#12	Yes	Male	Right
ex_hard_#3	part_#13	Yes	Male	Right
ex_hard_#4	part_#14	No	Male	Right
ex_hard_#5	part_#15	No	Male	Right
ex_hard_#6	part_#16	No	Male	Right
ex_hard_#7	part_#17	No	Male	Right
ex_hard_#8	part_#18	No	Male	Right
ex_hard_#9	part_#19	No	Male	Right
ex_hard_#10	part_#20	No	Male	Right
ex_soft_#1	part_#21	Yes	Male	Right
ex_soft_#2	part_#22	Yes	Male	Right
ex_soft_#3	part_#23	Yes	Male	Right
ex_soft_#4	part_#24	No	Male	Right
ex_soft_#5	part_#25	No	Male	Right
ex_soft_#6	part_#26	No	Male	Right
ex_soft_#7	part_#27	No	Male	Right
ex_soft_#8	part_#28	No	Male	Right
ex_soft_#9	part_#29	Yes	Male	Right
ex_soft_#10	part_#30	Yes	Male	Right

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